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TECHNICAL INVESTIGATION REPORT: SEALED MINI-NICKEL CADMIUM BATT--ETC(U)
SEP 82 J CRAWFORD, R S PINKHAM N68335-81-C-0502

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Romanov Mode	Ampere Hours
McCulloch Mode	Statistical Variance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of this effort indicate that no correlation could be established between any particular charging mode and any resulting enhanced cell capacity, all tested cells being considered. A further result was that the cells exhibited high variability of performance when compared to one which had outstanding stability under all test conditions. Further study is recommended to investigate the actual performance of batteries, using mini-nickel cadmium cells produced for field use. As a result, new standards for sealed mini-nickel

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cadmium cell performance should be evolved for future rechargeable battery systems.

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SUMMARY

A. GENERAL. The object of this program was to conduct an evaluation of charging techniques applicable to sealed mini-nickel cadmium batteries in the zero to five ampere-hour range. All tests and investigations were conducted on single Sub "C" classification cells of eight different manufacturers. The capacity of the cells tested was not greatly affected by any particular charge method. A further result was that cells exhibited higher variations of performance when compared to one which had outstanding stability under all test conditions. Further study is recommended to investigate the actual performance of batteries using mini-nickel cadmium cells produced for field use. As a result, new standards for sealed mini-nickel cadmium battery performance should be evolved for rechargeable battery systems.

B. PROCEDURES AND RESULTS.

1. Many approaches were reviewed in search for the optimum mode for charging sealed mini-nickel cadmium batteries. They were:

   a. Positive pulse mode

   b. Romanov mode (asymmetrical)

   c. McCulloch mode

   d. Constant current mode (for comparisons)

2. The key parameters selected and monitored for each charging mode were:

   a. Pulse frequency

   b. Average net charge rate

   c. Instantaneous charge pulse amplitude

   d. Pulse duty cycle

   e. Charging time

3. The positive pulse mode charging was conducted with a General Research Laboratories (GRL) positive pulse charger (GRL-P1). The Romanov mode charging was conducted with an asymmetrical pulse charger. The McCulloch mode charging was conducted with a GRL positive and negative pulse charger (GRL-P1/N). The constant current mode charging was conducted with a laboratory current regulated DC power supply. In each test the discharge was conducted with a constant current power supply driving a fixed load resistor in series with the cells under discharge. Measurement accuracy was within 1% for current and voltage.

4. A series of statistical analyses was conducted to indicate the relative merits of the four charging modes. Several parameters of significant importance constitute the bases of the analyses. The program of 66 different tests was performed on 10 cells. The output capacity of each cell in ampere hours was measured and the variations of output capacity were computed.

5. Table 1 shows each cell's maximum and minimum output capacities and the variation recorded during this program:

TABLE 1. TABLE OF RESULTS FOR MAXIMUM AND MINIMUM OUTPUT CAPACITY VALUES

CELL MFG	NO. OF TEST CYCLES PERFORMED*	OUTPUT CAPACITY: MAXIMUM METHOD OF CHARGE	MAXIMUM AH	MINIMUM METHOD OF CHARGE	MINIMUM AH	VARIATION BETWEEN MIN. & MAX.
GE	64	Positive Pulse & Romanov	1.10	Positive Pulse	0.90	0.20
SANYO	66	Constant Current & Asymmetrical	1.46	Asymmetrical	0.92	0.54
GOULD	66	Asymmetrical	1.[illegible]4	Constant Current	0.84	0.60
HITANICA	32†	Positive Pulse	1.51	Positive Pulse	0.85	0.66
PANANICA	66	Constant Current	1.72	Asymmetrical	1.02	0.70
SAFT B	66	Constant Current	1.50	Positive Pulse	0.78	0.72
SAFT L	66	Constant Current	1.56	Asymmetrical	0.83	0.73
MARATHON 1	44	Constant Current	1.40	Constant Current	0.28	1.12

* The above results were obtained during the course of 66 different tests.

† Introduced at cycle 35.

a. The GE cell was stable under all test conditions; it was remarkably consistent in output capacity, independent of the mode of charging, and had the lowest stability variance of output capacity. The Sanyo cell was second in stability; it maintained its capacity above 1 AH in 63 tests.

b. The Gould and Pananica cells improved with testing.

c. The Saft B and Saft L cells deteriorated after 39 and 50 test cycles respectively. The Saft L cell maintained 1 AH output capacity for 50 test cycles.

d. The Hitanica cell was subjected to the last 32 tests and maintained 1 AH output capacity until the next-to-last test.

e. The Marathon cell (Marathon 1) degraded after 25 tests (did not recover), and was removed from the test fixture after 44 test cycles. It was subsequently replaced by another Marathon cell (Marathon 2) in test 47; Marathon 2 tests are not included in the above table.

6. The test with widest variation of output capacity was with a high-rate constant current charge of 4 amps for 22.5 minutes, for a range of 0.64 to 1.38 AH (Test 64). The test with the minimum variation of output capacity was with a high-rate constant current charge of 6 amps for 14 minutes, for a range of 1.02 to 1.24 AH (Test 17).

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I. INTRODUCTION

A. The purpose of this investigation was to determine if an optimum method could be found to recharge mini-nickel cadmium battery cells. A review of practical techniques shows that charging equipment may be classified in four categories: direct current, positive pulse, asymmetrical, and positive pulse with negative pulse charging modes.

B. A group of cells was obtained from each of the following battery manufacturers: General Electric, Gould, Marathon, Hitanica, Pananica, Saft, and Sanyo. The cells were characterized at standard conditions and then subjected to numerous recharge regimes to see if any significant changes in performance could be found.

II. EQUIPMENT AND PROCEDURES

A. EQUIPMENT. The equipment listed in Table 2 was used during this program:

TABLE 2. TEST EQUIPMENT

ITEM	MANUFACTURER	MODEL NO.	SERIAL NO.
VOLTAGE & TIME DATA LOGGER	DORIC	205	20560
USE: To record charge voltage of each cell and length of time on charge, and to record discharge voltage and time of each cell down to 1 VDC minimum.			
PULSE CHARGER	GEN'L RESEARCH LABS	GRL-P1	1
USE: To generate positive charge pulses by controlling frequency, duty cycle, and amplitude of positive charge pulses.			
PULSE CHARGER	GEN'L RESEARCH LABS	GRL-P1/N	1
USE: To provide McCulloch pulse positive and negative duty cycles.			
POWER SUPPLY,DC CONSTANT CURRENT	HEWLETT-PACKARD	6024A	2126A-006A
USE: To generate constant current charge currents by controlling the charge currents to fixed values.			
ROTARY FAN	ROTRON	SPRITE SU2A11	028267
USE: To cool discharge load resistor during constant current discharges.			
RESISTOR, 10 OHM, 200 WATT	CLAROSTAT	VK200WA	-
USE: As a load resistor to control discharge current at fixed, constant rate of 1.2 amps for the 9 cells in series.			
DIGITAL MULTIMETER	WESTON	6000	040
USE: To measure constant current charge current and discharge current in amps.			
DIGITAL STORAGE OSCILLOSCOPE	GOULD	OS4020	448/185
USE: To measure charge pulse amplitude in amps, frequency in Hz, and duty cycles of positive pulse, Romanov pulse, and McCulloch pulse charge pulses. Also used to plot charge pulse configurations on Esterline-Angus Model MS401B chart recorder from oscilloscope display.			
CHART RECORDER	ESTERLINE-ANGUS	MS401B	S-22087-1A
USE: To record charge current of constant current charges and cell voltages during discharge.			
DIGITAL MULTIMETER	WESTON	6502	758
USE: To measure maximum and minimum voltages of cells charged.			

B. DESCRIPTION AND OPERATION OF SEALED NICKEL-CADMIUM CELLS

1. The nickel-cadmium cell is an electrochemical system in which the electrodes containing the active materials undergo changes in oxidation state without any change in physical state. These active materials are highly insoluble in alkaline electrolyte. They remain as solids and do not dissolve while undergoing changes in oxidation state. Because of this the electrodes are long-lived, since no chemical mechanism which would cause the loss of active materials exists.

2. An important cell characteristic which results from these physical and other properties is that the cell potential is essentially constant throughout nearly all of the discharge. In the nickel-cadmium cell, nickel hydroxide is the active material in the positive plate. During discharge the charged nickel hydroxide NiOOH goes to a lower valence state, Ni $(OH)_2$, and releases electrons to the external circuit. During charging of the battery, these reactions are reversed. The net overall reactions which occur in the KOH electrolyte can be expressed as follows:

$$\underset{\text{positive electrode}}{2NiOOH + 2H_2O} + \underset{\text{negative electrode}}{Cd} \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} \underset{\text{positive electrode}}{2Ni(OH)_2} + \underset{\text{negative electrode}}{Cd\,(OH)_2}$$

3. A typical sealed-mini-nickel cadmium cell uses a cylindrical nickel-plated steel case as the negative terminal and a cell cover as a positive terminal. The plates, which are wound to form a compact roll, are isolated from each other by a porous separator. An insulating seal ring separates the positive cover from the negative cover (as shown in Figure 1). Cylindrical cell construction relies upon a tab or edge welded multiple connection for electrode current conduction from both positive and negative spiral-wound plates.

4. Figure 2 presents a typical cell specification sheet.

C. DESCRIPTION OF CHARGERS FOR SEALED NICKEL-CADMIUM CELLS

1. To recharge a nickel-cadmium battery, a DC component of current must be applied in a reverse direction to the discharge polarity. The product of the average value of the applied current in amperes and the time of duration in hours is the ampere hour input, AH. Various types of chargers can be obtained or designed to suit particular operational requirements. Factors to be considered are: recharge time, method of charge control (if any) size, weight, input power, environmental conditions, and commercial or military specification requirements.

2. Simple chargers for nickel-cadmium batteries can be half- or full-wave rectified, filtered or unfiltered, regulated or unregulated current limited AC line power supplies. They can be configurated to slow (trickle) charge in 10 to 18 hours. Faster recharge times, from 10 hours down to 15 minutes, require additional design features and active end-of-charge cutoff controls.

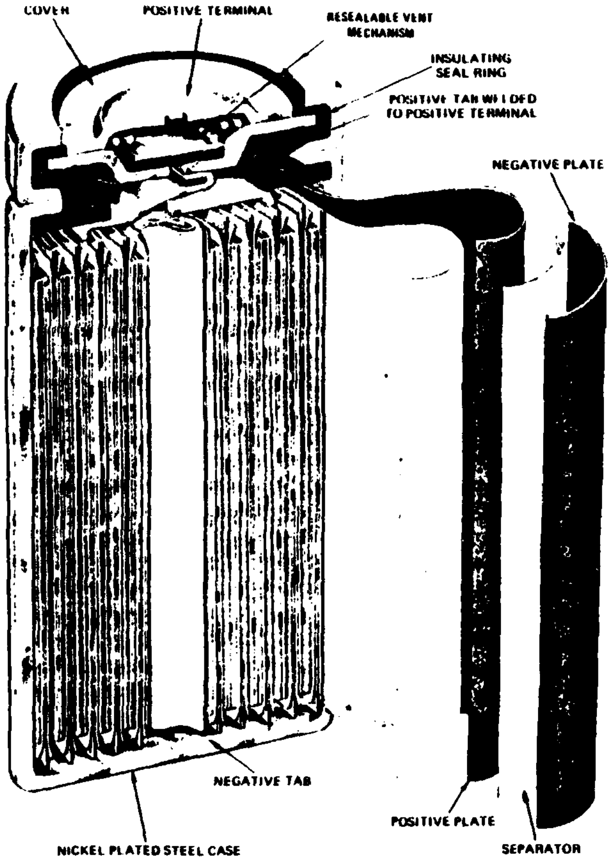

FIGURE 1. CYLINDRICAL CELL CONSTRUCTION

TYPICAL CELL SPECIFICATION SHEET

RECHARGEABLE
NICKEL-CADMIUM BATTERIES

Cell Size - C_s

ANSI Designation - KR 222/412

Cell Type - STANDARD

ELECTRICAL SPECIFICATIONS

Voltage	
* Rated volts d-c	1.2
Capacity (Ah) at 25°C to 0.9V	
* Rated minimum at 1.2A (C) Rate	1.0 - 1.2
Expected minimum at 240 mA (C/5) Rate	1.3
Charge Rate (mA) at 25°C	
* Maximum rate in overcharge	120
Minimum charge rate	60
**Max. Discharge (A) at 25°C	
Continuous	29
Momentary (1 second)	58
***Cell Temperature Limits (°C)	
Storage	-40° to +50°
Cell under discharge	-20° to +50°
Cell under charge at 120mA	+5° to +50°
Effective Internal Resistance Re (milliohms)	
* Rated maximum	25
Typical	21
Weight	
Typical (ounces)	1.5
(grams)	42.5

MECHANICAL DIMENSIONS

Dimensions	MAXIMUM DIMENSIONS BARE CELL Inches	mm	SLEEVE & TAB Inches	mm
Diameter	0.875	22.23	0.93	23.6
Height	1.620	41.15	1.66	42.2

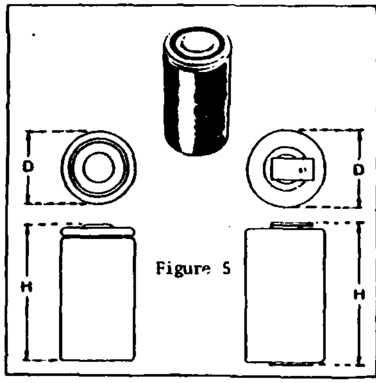

Figure 5

* Per American National Standard (ANSI) C18.2-1977.

**Maximum continuous discharge current may be further limited due to cell temperature rise and the associated impact on battery life. In addition to discharge current, temperature rise is dependent on duration of discharge, discharge duty cycle and the thermal characteristics of multicell battery designs.

***Temperature measured on the cell case. Higher temperatures may be used but will result in reduced battery life.

FIGURE 2. TYPICAL CELL SPECIFICATION SHEET

3. As varied as the battery application becomes, so does the charger. Designing a battery system mandates careful selection or design of an appropriate charging power supply.

4. The cell manufacturers can supply significant data to assist in the initial determination of the design effort, but specific testing and data must be generated before a final design is selected for use. Battery application specialists and firms experienced with battery power supply manufacturing are available to assist in these efforts or to support in-house design work.

5. Fast chargers, one hour or less, must be capable of sensing battery or selected cell pressure, temperature, voltage or combinations of these parametric changes to effect reliable and safe charge control. Cell voltages alone vary too widely for serious technical considerations. Temperature sensed on each cell seems tractable if the charge rate does not exceed the thermal rate of rise for tracking of internal cell pressure buildup.

6. Pressure sensing is extremely useful and reliable if room is available for the incorporation of the required pressure transducers and/or pressure adaptors and switch housings. A careful study of all factors can result in a reliable, survivable, rechargeable nickel-cadmium battery pack.

D. DESCRIPTION OF LABORATORY PROCEDURES. Figures 3 and 4 present block diagrams of the charging and discharge equipment setups.

1. CHARGING. The sealed mini-nickel cadmium battery is charged by applying a direct current of proper polarity to the battery. The charging current can be pure DC or contain a significant ripple component, half- or full-wave rectified DC or some type of pulsating DC waveform.

a. The modes of charging used for this program were Romanov, constant current, McCulloch, and positive pulse as follows:

(1) Romanov Mode (Asymmetrical)

(a) To effect the Romanov mode a charging circuit was configured as shown in Figure 5, an autotransformer (T_1) was used to adjust the input line voltage to a step-down transformer (T_2). The current path of power diode CR_1 and adjustable resistor R_1 determines the positive portion of charging current and is measured as I_2. The negative portion is determined by CR_2 and R_2 and is measured as I_1.

(b) The composite charging current is measured as I_3. A typical waveform is shown in Appendix A. The ratio of positive-to-negative current is selected and set by adjusting R_1 and R_2. Fine control of the total charge current is obtained by adjusting the autotransformer.

(2) Constant Current Mode. Constant current charging is the charging of a cell or battery at a value of current which will have only minor changes in magnitude from the start of charge and throughout the charge period. Constant current charging was accomplished by using a DC regulated laboratory power supply (as shown in Figure 6).

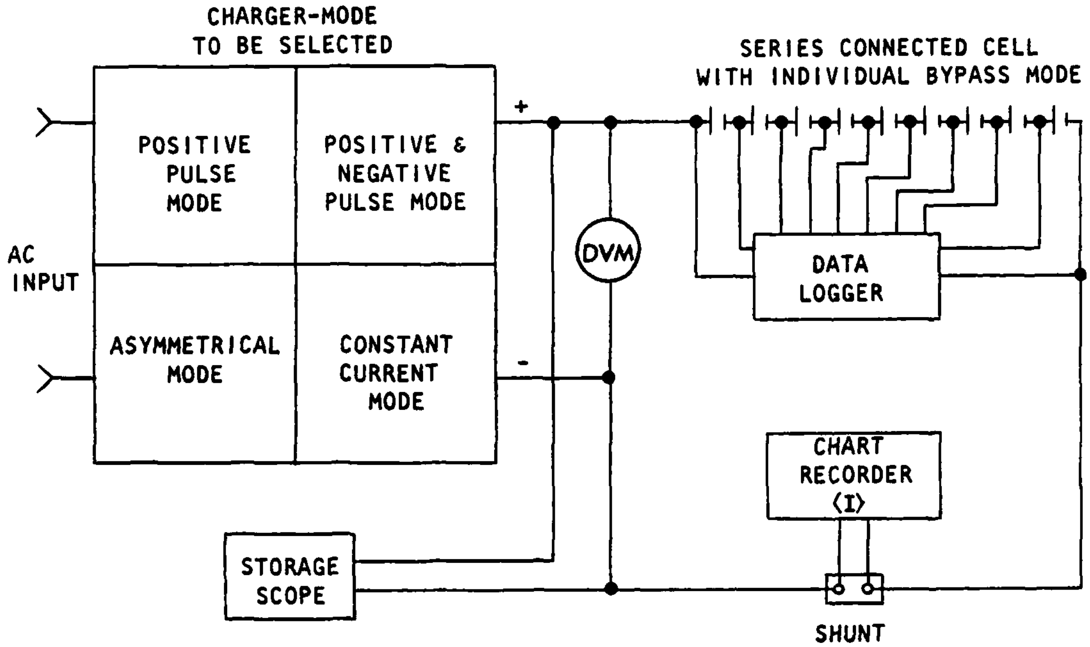

FIGURE 3. BLOCK DIAGRAM OF "SUB C" CELL CHARGING EQUIPMENT SETUP

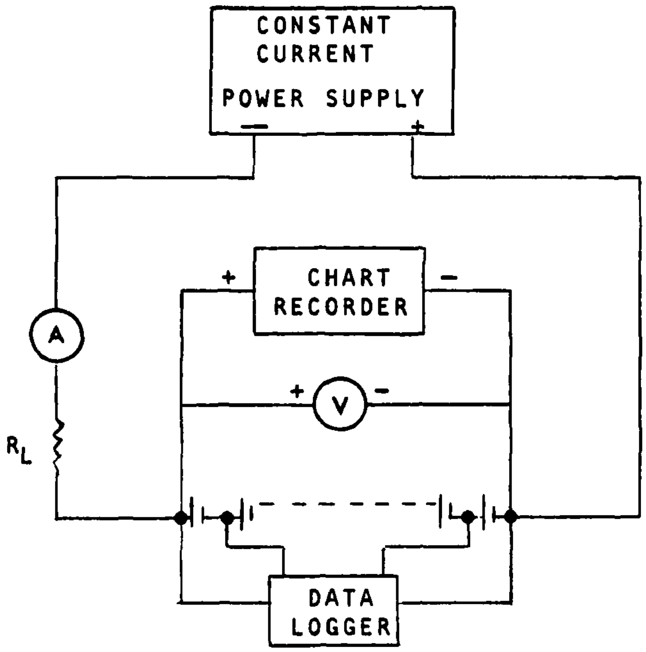

FIGURE 4. BLOCK DIAGRAM OF DISCHARGE EQUIPMENT SETUP

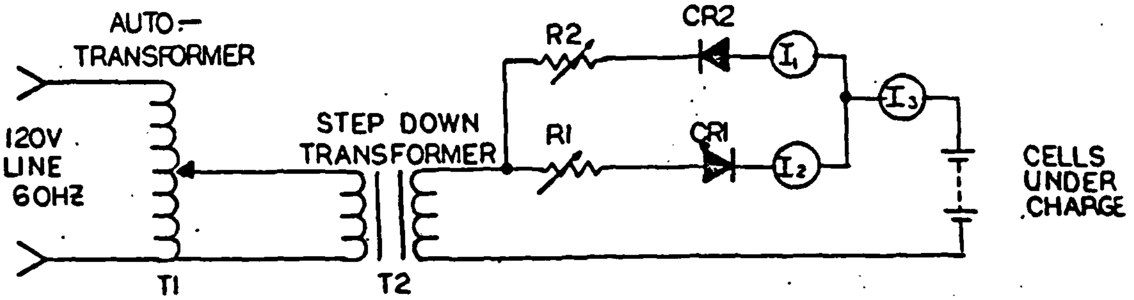

FIGURE 5. SCHEMATIC OF ASYMMETRICAL WAVEFORM CHARGER

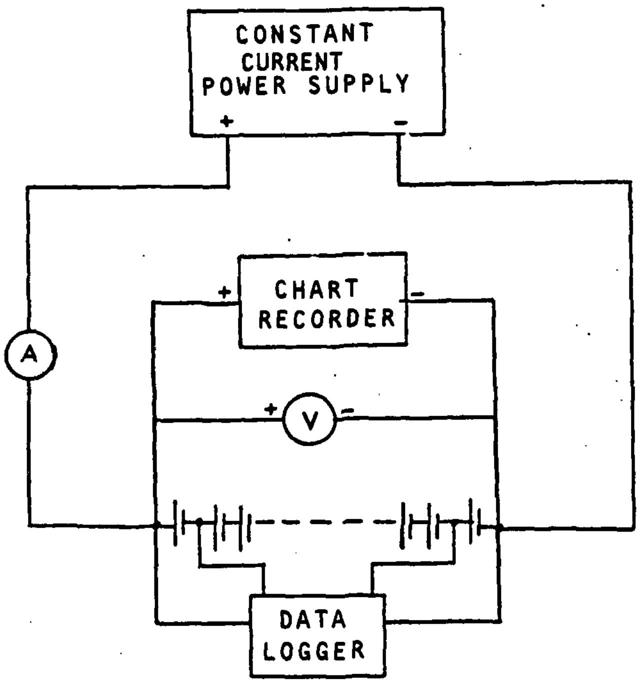

FIGURE 6. BLOCK DIAGRAM OF CONSTANT CURRENT CHARGING

(3) McCulloch Mode (Positive and Negative).

(a) To effect the positive and negative pulse mode, a charging circuit was configured as shown in Figure 7. The positive and negative pulse charger converts 115 VAC into an adjustable source of battery charging pulses. The AC power is applied to a DC switching power supply.

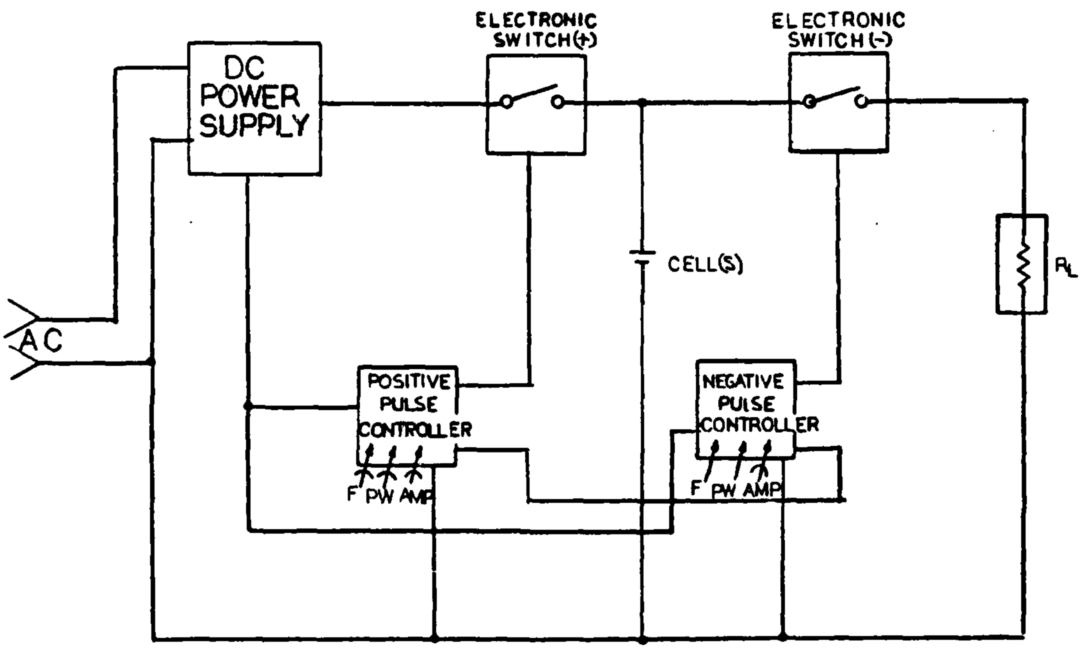

FIGURE 7. BLOCK DIAGRAM OF MCCULLOCH (POSITIVE AND NEGATIVE) PULSE CHARGER

(b) The constant voltage DC output of the switching power supply is applied across a series combination of load and electronic switch (switching transistor). The electronic switch is turned on and off at the selected frequency with pulse duration and amplitude, corresponding to the positive pulse controller and negative pulse controller. A typical waveform is shown in Appendix A.

(4) Positive Pulse Mode. To effect the positive pulse mode, a charging circuit was configured similar to that used for the positive and negative mode, except that only the positive portion of the controller was used.

b. During each charge, individual cell voltages and the length of charge time were recorded as follows:

(1) Charge pulses were measured by the Gould digital storage oscilloscope for pulse amplitude, pulse frequency, and duty cycle. From the oscilloscope's memory, the Esterline-Angus chart recorder plotted the charge pulse configuration.

(2) The Esterline-Angus chart recorder also recorded the charge current of the constant current charges and the cell voltages. Maximum and minimum cell voltages were measured and recorded by the Weston Model 6502 digital multimeter.

(3) The Weston Model 6000 digital multimeter measured and set the charge current.

(4) The time of charge and the increase in cell voltage of each cell were measured and recorded by the Doric data logger each hour for charges at low rate and every ten minutes for charges at high rate. For high-rate charges of 22.5 minutes, however, these items were measured and recorded every 5 minutes. During high-rate charges, the cell voltages and charge time were also recorded manually by the test engineer.

(5) When the required time of charge was completed for the rate of charge, the charger was switched out of the charge circuit and the "open circuit voltage" of each cell was measured and recorded by the Doric data logger.

2. <u>DISCHARGING</u>. The cells were rested for one hour after charge, and then discharged by the regulated discharge method shown in block diagram form, in Figure 4, page 10, with a constant current power supply through a 10-ohm resistor at a constant rate of 1.2 amperes.

a. The regulated discharge power supply was switched into the circuit after the one-hour rest, and the cell voltages and the start of discharge time were recorded on the Doric data logger, which was then programmed to record at ten-minute intervals from the start of discharge. The voltages of the cells were also manually monitored and recorded by the test engineer.

b. When a cell decreased in voltage to 1.0 VDC, it was switched out of the discharge circuit and bypassed. This time was recorded by manual activation of the data log function of the data logger. The cell capacity was then calculated by the discharge rate multiplied by the discharge time. The discharge time in minutes was converted to hours. When 8 cells had discharged to 1.0 VDC and been switched out of the ciruit, the voltage of the remaining cell was monitored by the test engineer; when it reached 1.0 VDC, the regulated discharge power supply was switched out of the discharge circuit. All nine cells were then switched into the discharge circuit and the "open circuit voltage" was measured and recorded for each cell.

III. RESULTS AND ANALYSIS

A. RESULTS

1. During this program, a total of 495 tests were conducted. Table 3 breaks down the tests by cells:

TABLE 3. CELL TESTS

TEST MODE & TYPE CHARGE	NO. OF TESTS										
	DE-SIRED	MAR 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	TOTALS
CONSTANT DC											
High	17	17	17	17	17	17	17	17	4	1	124
Trickle	11	11	11	11	10	11	11	11	5	1	82
PULSE +											
High	9	9	9	9	9	9	9	9	3	0	66
Trickle	14	14	14	14	13	14	14	14	5	0	102
ASYMMETRICAL											
High	2	1	2	2	2	2	2	2	2	0	15
Trickle	3	2	3	3	3	3	3	3	3	0	23
PULSE +/-											
High	5	5	5	5	5	5	5	5	5	2	42
Trickle	5	5	5	5	5	5	5	5	5	1	41
TOTAL TESTS	66	64	66	66	64	66	66	66	32	5	495

2. The output capacity results of all tests are presented in Appendix B (8 sheets). The charge curves of all cells were combined on one graph for each test and are presented in Appendix C. The same was done with the discharge curves which are presented in Appendix D. Computer plots of point-by-point data of output capacity versus test number are shown in Appendix E. The data was analyzed for statistical significance, and the results of this analysis are presented in this section. In summary, performance of the cells was as follows:

a. Saft B and Saft L cells degraded badly over the course of testing.

b. Gould and Pananica cells improved with testing.

c. GE cell (#4 above) was remarkably stable during all test conditions. A second GE cell (#9 above) was added to the testing schedule for verification of test data at test number 62.

d. Sanyo cell was second to the GE cell in stability.

e. The first Marathon cell degraded after 25 tests (did not recover), and was removed from the test fixture after 44 test cycles. The second Marathon cell was subjected to 20 tests.

f. Hitanica cell was subjected to the last 32 tests and maintained 1 ampere hour output capacity until the next-to-last test.

B. DATA ANALYSIS (STATISTICAL REVIEW)

1. The GE cell was remarkably stable under all experimental conditions. The next most stable cell, the Sanyo, gave a variance ratio relative to the GE of approximately 6.04 which is significant at well over one part in a thousand. Some cells showed a pronounced degradation over the course of testing (most notably the Saft B and Saft L), and some cells exhibited a tendency to stabilize (in particular the Gould).

2. The data of Appendix B was reworked as follows:

a. The Marathon cell data was dropped (the cell failed).

b. One aberrant value of 0.6 was omitted from the Saft B measurements.

c. Two values (the lowest) known to be faulty were omitted from the GE data (a poorly soldered connection had been located in the test jig and repaired). This left 7 time series to be examined; the smallest (Hitanica) contained 32 tests; most had 66. Each series was smoothed by taking running medians of 3 (consecutive data points). This was repeated until there was no change. Next running triples were averaged using weights 1,2,1. Thus 1,3,2, 4,5,4,2,0 becomes 1,2,3,4,4,4,2,0 and finally 1,2,3,3.75,4,3,5,2,0. These 7 smoothed time series are displayed in Appendix F.

d. Histogram plots which indicate a normal distribution for the cell data are presented in Appendix G.

e. An assessment was then made of the normality of the distribution of the values for each of the time series. That is, we tested whether it is reasonable to assume that the fraction of values less than x is given by

$$\mathrm{Gau}((x-\mu)/\sigma)$$

where

$$\mathrm{Gau}(z) = \int_{-\infty}^{z} \exp\left(-\frac{t^2}{2}\right)\frac{dt}{\sqrt{2\pi}}$$

The values for each time series were arranged in order of size and the nine deciles (*) for the standard normal. Plots which are reasonably straight indicate an approximate normal or Gaussian distribution. Probability plots are presented in Appendix H. Finally, since these plots are reasonably straight, one may employ F tests (probability tests) to compare the variances for each series of values, and thereby assess the relative stability of each series. An examination of the smoothed time series makes a number of points obvious: the Saft cells both degraded badly over the course of the experiments; the Gould cell actually improved; the Pananica cell improved over much of the range, but fell off at the end. Table 4 gives variances for each of the time series:

(*) The i^{th} decile d(i) for the normal distribution is that real number such that Gau(d(i)) - (i-1/2)/10, whereas the decile D(i) for the data is a value such that i/10 of the observed values are less than or equal to D(i) and (10-i)/10 bigger than or equal to D(i).

TABLE 4. TABLE OF VARIANCES

Manufacturer	Variance	N	Ratio (Var/GE)
GE	.00117	64	1.0
Sanyo	.00707	66	6.04
Gould	.0110	66	9.4
Pananica	.0206	66	17.6
Saft L	.0224	66	19.1
Saft B	.0390	65	33.0
Hitanica	.0701	32	59.9

The variance as a measure assesses variability, and clearly the GE cell is far more stable than any of the others. Variances are computed via

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y})^2$$

where n is the number of observations, and

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i$$

This so-called F ratio with 65 degrees of freedom in the numerator and 63 degrees of freedom in the denominator is significant at well over one in a thousand. The other F ratios, 9.4, 17.6, ... are even more so. Thus the GE cell is really very different from the others (more stable and consistent in output capacity).

f. On the other hand

$$\frac{\text{Var(Pan)}}{\text{Var(Gld)}} = 1.87 = F,$$

and this is not significant at, say, the 2.5% level, and these two cells may be regarded as equally variable (or stable). The graphs in Appendix H make clear not only the stability of the GE cell but the tendency for the Pananica and especially Gould cells to improve. Clearly the Saft cells are degrading over the course of the experiment.

C. CALCULATIONS

1. The input capacity of Sub "C" cells in ampere hours was calculated as follows:

Ampere hours of input capacity = (net average current) x (hours of charge)

where

$$\text{Net average current } (I_{ch}) = \frac{1}{T}\left[\int_{0}^{t_+} i_+(t)dt - \int_{t_+}^{t_-} i_-(t)dt\right]$$

2. The output capacity of Sub "C" cells was calculated by multiplying:

(Discharge constant current) x (hours of discharge) = output ampere hours.

3. The fixed load resistor to control discharge current at a constant rate was determined by the ratio of:

DC voltage of cells in series (OCV)/1.2 ampere
constant current = fixed resistive load

$$R_L = \frac{V_{DC}}{I_{CC}}$$

$0-t_+$ = Pulse width of positive portion

$t_- - t_+$ = Pulse width of negative portion

$T = \frac{1}{F}$ = Period of waveform

IV. CONCLUSIONS

A. For sealed mini-nickel cadmium cells there is no significant difference in the ampere hour output capacity as a function of charge input techniques. The result of this study reinforces earlier investigations. However, our study has shown wide variability among the tested manufacturers individual cell performance as measured by output capacity with cycling.

B. The General Electric cell had greatly superior stability characteristics as compared to most of the other cells tested. Its variance was a minimum of 6 times to a maximum of 60 times less than the other cells tested.

C. The characteristics of cells can be typed to a particular manufacturer. When this data is known, an effective charge system can be implemented.

V. RECOMMENDATIONS

A. As a result of this work, it is recommended that similar variance studies be performed on all cells and batteries made by various manufacturers.

B. New charge control techniques should be investigated to minimize variance in battery performance. These studies and their results will lead to improved reliability in field use battery systems.

C. Pressure control switches and electronic peripheral protection circuits, for example, are now available for end-of-charge and for end-of-discharge control. One such unit containing these controls is Model BB-542/U, manufactured by Frezzolini Electronics Inc., Hawthorne, NJ, and is now in use for military radio communications. It is recommended that this technology be used for all future sealed mini-nickel cadmium battery system applications.

VI. BIBLIOGRAPHY

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(3) General Electric Specification Sheet for Nickel-Cadmium Batteries BBD-OEM-1812-Rev 1

(4) Johnson, Robert R. "Elementary Statistics", Second Edition, North Scituate, Massachusetts, Duxbury Press, 1976

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APPENDIX A - TYPICAL CHARGING WAVEFORMS

TEST NO. 45 - CHARGED AT $I_{Average}$ = 0.150 Amperes

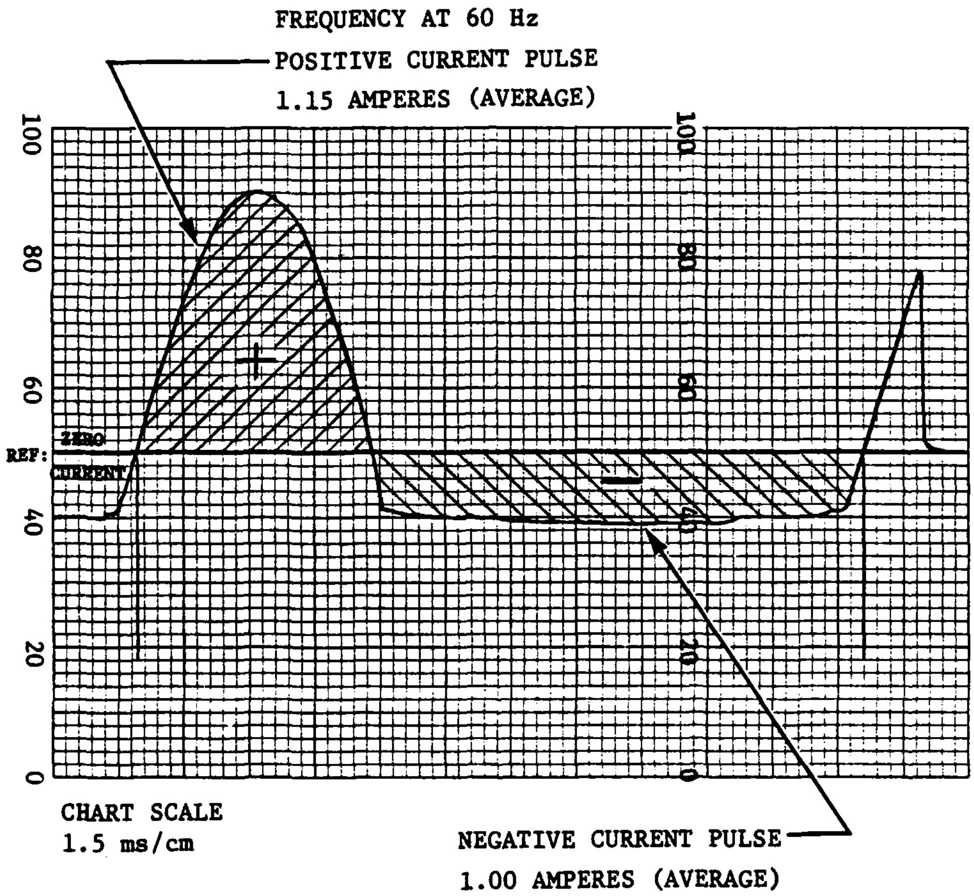


FIGURE A-1. TYPICAL CURRENT CHARGING WAVEFORM ASYMMETRICAL

NAEC-92-161

TEST NO. 64 - CHARGED AT $I_{average}$ = 0.20 Amperes

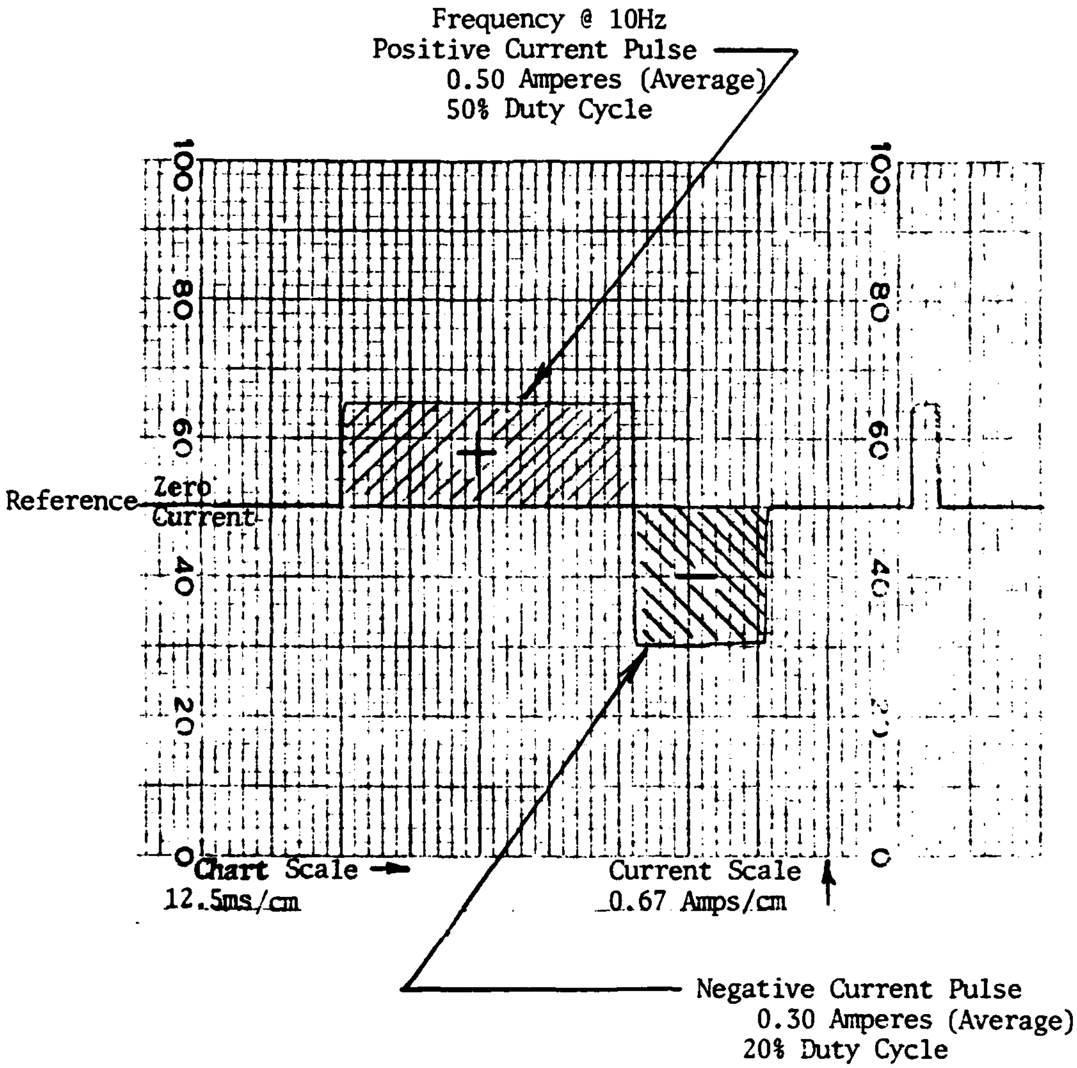


FIGURE A-2. TYPICAL CURRENT CHARGING WAVEFORM MCCULLOCH (POSITIVE/NEGATIVE)

TEST NO. 22 - CHARGED AT $I_{Average}$ = 0.080 Amperes

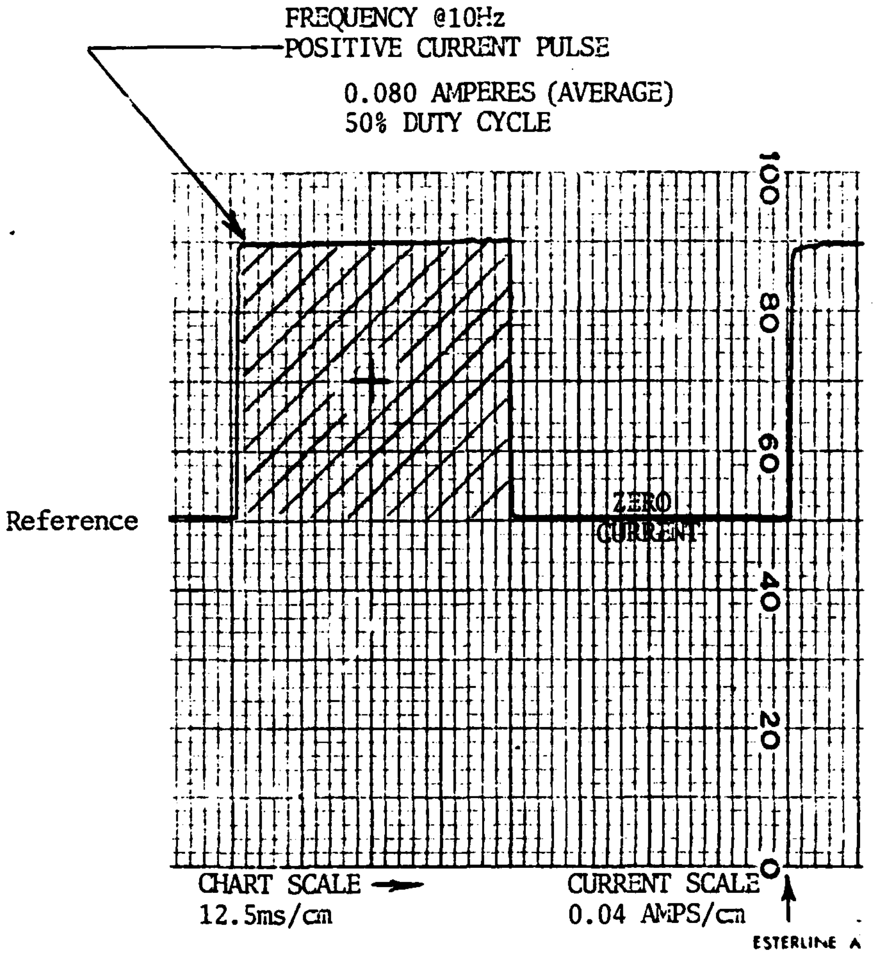


FIGURE A-3. TYPICAL CURRENT CHARGING WAVEFORM POSITIVE PULSE

APPENDIX B - OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 1 Charged for 75 hours at a trickle charge at 60 Ma.	1.33	1.33	1.33	1.00	1.58	1.41	1.25			1.0
TEST 2 Charged for 1 hour 15 minutes at 1.2 Amps constant current	1.18	1.30	1.30	1.02	1.42	1.32	1.20			1.0
TEST 3 Charged for 1 hour 10 minutes at 1.2 Amps constant current	1.14	1.26	1.28	1.02	1.34	1.26	1.12			1.2
TEST 4 Charged for 1 hour 10 minutes at 1.2 Amps constant current	1.08	1.21	1.24	.98	1.31	1.21	1.06			1.2
TEST 5 Charged for 57 Min. at 7 Hz and a 50% duty Hz at 1.2 Amps pulse	1.08	1.20	1.21	1.00	1.28	1.23	1.01			1.0
TEST 6 Charged for 1 hour at 1.2 Amps constant current	1.10	1.12	1.14	1.02	1.20	1.16	.92			1.2
TEST 7 Charged for 1 hour at 1.2 Amps constant current	1.10	1.16	1.14	1.04	1.20	1.18	.94			1.2
TEST 8 Charged for 17 hours at a trickle charge at 100 Ma	1.18	1.34	1.42	1.00	1.46	1.30	1.22			1.2
TEST 9 Charged for 1 hour 4 minutes at 1.2 Amps constant current	1.12	1.16	1.16	1.00	1.26	1.20	1.14			1.2

PRECEDING PAGE B

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	DISCHARGE RATE (AMPS)
TEST 10 Charged for 37 minutes at 2 Amps constant current	1.08	1.12	1.08	.96	1.22	1.14	.90			1.2
TEST 11 Charged for 22 minutes at 3 Amps constant current	1.06	1.10	1.12	1.02	1.14	1.12	.84			1.2
TEST 12 Trickle charged for 16 hours at 86 Ma.	1.14	1.28	1.26	1.00	1.36	1.26	1.20			1.2
TEST 13 Charged for 20 minutes at 4 Amps constant current	1.12	1.20	1.14	1.02	1.30	1.24	1.18			1.2
TEST 14 Charged for 29 minutes at 3 Amps constant current	1.20	1.30	1.28	1.04	1.44	1.34	1.24			1.2
TEST 15 Charged for 21 minutes at 4 Amps constant current	1.18	1.28	1.20	1.06	1.40	1.32	1.18			1.2
TEST 16 Charged for 17 minutes at 5 Amps constant current	1.10	1.20	1.08	1.02	1.26	1.24	1.10			1.2
TEST 17 Charged for 14 minutes at 6 Amps constant current	1.06	1.18	1.02	1.02	1.20	1.24	1.12			1.2
TEST 18 Trickle charged for 20 hours at 80 Ma.	1.18	1.34	1.34	1.00	1.46	1.28	1.22			1.2

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 19 Trickle charged for 18 hours at 80 Ma.	.60	.60	1.10	1.00	1.40	1.24	1.10			1.2
TEST 20 Trickle charged for 3 hours at 900 Ma. and 15 hours at 50 Ma.	1.40	1.50	1.56	1.08	1.72	1.46	1.28			1.2
TEST 21 Pulse charged for 21 hours at 50% duty cycle, 20 Hz at 80 Ma.	1.00	1.20	1.28	1.10	1.40	1.28	1.24			1.2
TEST 22 Pulse charged for 67 hours at 50% duty cycle, 10 Hz at 80 Ma.	1.10	1.32	1.50	1.10	1.58	1.32	1.28			1.2
TEST 23 Pulse charged for 18 hours 30 min. at 50% duty cycle, 5 Hz at 90 Ma.	1.08	1.18	1.34	1.00	1.48	1.20	1.24			1.2
TEST 24 Charged for 24 hours at 25% duty cycle, 5 Hz at 50 Ma pulse	1.08	1.26	1.32	1.04	1.50	1.44	1.32			1.2
TEST 25 Charged for 14 hours at 25% duty cycle, 5 Hz at 150 Ma pulse	0.96	1.00	1.24	1.00	1.51	1.23	1.21			1.2
TEST 26 Charged for 1-1/4 hour at 25% duty cycle, 5 Hz 1.2 ampere pulse	0.83	1.14	1.14	0.98	1.38	1.22	1.25			1.2
TEST 27 Charged for 14 hours at 25% duty cycle, 10 Hz at 150 Ma pulse	0.84	1.06	1.16	1.00	1.46	1.19	1.24			1.2

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 28 Charged for 1 hour 15 min at 25% duty cycle, 10 Hz at 1.2 ampere pulse	0.70	0.97	1.06	0.90	1.39	1.10	1.20			1.2
TEST 29 Charged for 14 hours at 25% duty cycle, 20 Hz at 150 Ma pulse	0.84	1.06	1.13	1.02	1.49	1.19	1.27			1.2
TEST 30 Charged for 62 hours at 25% duty cycle, 60 Hz at 25 Ma pulse	0.80	1.08	1.14	1.06	1.52	1.20	1.28			1.2
TEST 31 Charged for 1-1/4 hour at 25% duty cycle, 60 Hz at 1.25 ampere pulse	0.55	1.11	1.15	1.04	1.45	1.25	1.25			1.2
TEST 32 Charged for 14 hours at 25% duty cycle, 120 Hz at 150 Ma pulse	0.67	1.07	1.11	1.04	1.56	1.16	1.28			1.2
TEST 33 Charged for 1 hour 15 min at 25% duty cycle, 120 Hz at 1.20 ampere pulse	0.60	1.07	1.15	1.03	1.45	1.20	1.26			1.2
TEST 34 Charged for 1 hour at 25% duty cycle, 240 Hz at 2.00 ampere pulse	0.68	1.12	1.15	1.08	1.46	1.28	1.28			1.2
TEST 35 Charged for 14 hours at 25% duty cycle, 240 Hz at 150 Ma pulse	0.67	0.97	1.06	0.98	1.44	1.16	1.21	1.31		1.2
TEST 36 Charged for 1 hour at 25% duty cycle, 480 Hz at 1.5 ampere pulse	0.49	1.02	1.13	1.03	1.38	1.25	1.25	1.46		1.2

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 37 Charged for 15 hours at 25% duty cycle, 480 Hz at 200 Ma pulse	0.66	1.00	1.10	1.04	1.51	1.25	1.27	1.51		1.2
TEST 38 Charged for 1 hour at 25% duty cycle, 600 Hz at 1.5 ampere pulse	0.58	1.02	1.13	1.04	1.40	1.27	1.30	1.48		1.2
TEST 39 Charged for 14 hours at 25% duty cycle, 600 Hz at 150 Ma pulse	0.65	1.02	1.13	/	1.54	1.28	1.30	1.45		1.2
TEST 40 Charged for 1 hour at 1.5 Amps constant current	0.47	0.96	1.09	1.02	1.34	1.25	1.25	1.39		1.2
TEST 41 Charged for 60 hours at 105 Ma constant current	0.43	0.94	1.12	/	1.67	1.28	1.32	1.44		1.2
TEST 42 Charged for 22-1/2 minutes at 4A constant current	0.08	0.92	1.10	1.04	1.39	1.32	1.28	1.46		1.2
TEST 43 Charged for 22-1/2 minutes at 4A constant current	0.10	0.97	0.95	1.06	1.02	1.24	1.19	1.28		1.2
TEST 44 Charged for 14 hours at 150 Ma constant current	0.28	0.95	1.07	1.04	1.45	1.27	1.25	1.38		1.2
TEST 45 Charged for 14 hours at 150 Ma. 60 Hz, asymmetrical pulse		0.98	1.07	1.02	1.48	1.28	1.26	1.28		1.2

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 1 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 46 Charged for 1-1/2 hours at 1.25 Amps 60 Hz, asymmetrical pulse		0.94	1.13	1.02	1.67	1.46	1.44	1.42		1.2
TEST 47 Charged for 12 hours at 150 Ma. 60 Hz, asymmetrical pulse	MAR 2 1.13	0.89	1.01	1.03	1.51	1.30	1.36	1.15		1.2
TEST 48 Charged for 1 hour 20 min. at 1.2 Amps, 60 Hz, asymmetrical pulse	1.33	0.91	0.90	1.10	1.46	0.92	1.33	1.31		1.2
TEST 49 Charged for 14 hours at 150 Ma constant current	1.31	0.88	1.04	1.04	1.44	1.24	1.24	1.09		1.2
TEST 50 Charged for 37 hours at 50 Ma 60 cycles, 50% duty cycle	1.31	0.86	1.02	1.03	1.43	1.26	1.25	1.07		1.2
TEST 51 Charged for 35 minutes at 2 Amps, 60 Hz, 50% duty cycle	1.13	0.78	0.83	0.95	1.19	1.09	1.13	0.85		1.2
TEST 52 Charged for 25 minutes at 4 Amps, constant current	1.27	0.80	0.95	1.00	1.07	1.20	1.18	1.01		1.2
TEST 53 Charged for 3 hours at 900 Ma constant current, and 15 hours at 50 Ma constant current	1.37	0.84	0.96	1.06	1.45	1.21	1.27	0.92		1.2
TEST 54 Charged for 14 hours at 25% duty cycle, 20 Hz, 125 Ma	1.26	0.82	0.95	1.06	1.39	1.16	1.25	0.94		1.2

OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

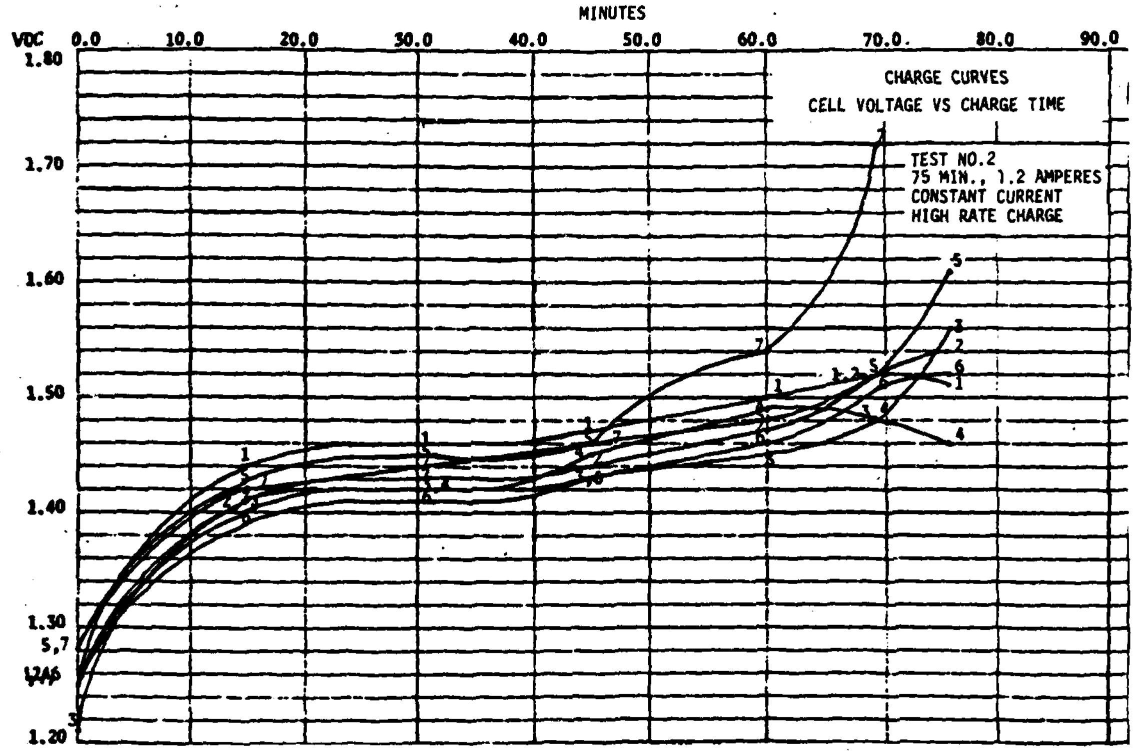
TEST NO./DESCRIPTION	AMPERE HOURS OUT									DISCHARGE RATE (AMPS)
	MAR 2 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	
TEST 55 Charged for 16 hours, 25% positive 25% negative duty cycle 10 Hz, 150 Ma	1.28	0.82	0.92	1.03	1.39	1.15	1.22	0.96		1.2
TEST 56 Charged for 62 hours, 50% positive 50% negative duty cycle, 10 Hz, 100 Ma	1.31	0.84	0.92	1.04	1.38	1.16	1.22	1.00		1.2
TEST 57 Charged for 1 hour 10 minutes, 50% positive, 50% negative duty cycle, 10 Hz, 1.25 Amperes	1.27	0.84	0.96	1.04	1.27	1.19	1.22	0.97		1.2
TEST 58 Charged for 11 hours 30 minutes 50% positive, 50% negative duty cycle, 10 Hz, 150 Ma	1.26	0.80	0.95	1.03	1.38	1.20	1.28	0.97		1.2
TEST 59 Charged for 1 hour 10 minutes, 1.2A DC with 10 Hz, positive and negative pulse	1.27	0.77	0.96	1.03	1.27	1.21	1.22	0.94		1.2
TEST 60 Charged for 14 hours 20 minutes, 50% positive, 50% negative pulse 200 Ma, 5 Hz	1.28	0.82	0.98	1.04	1.40	1.22	1.25	0.97		1.2

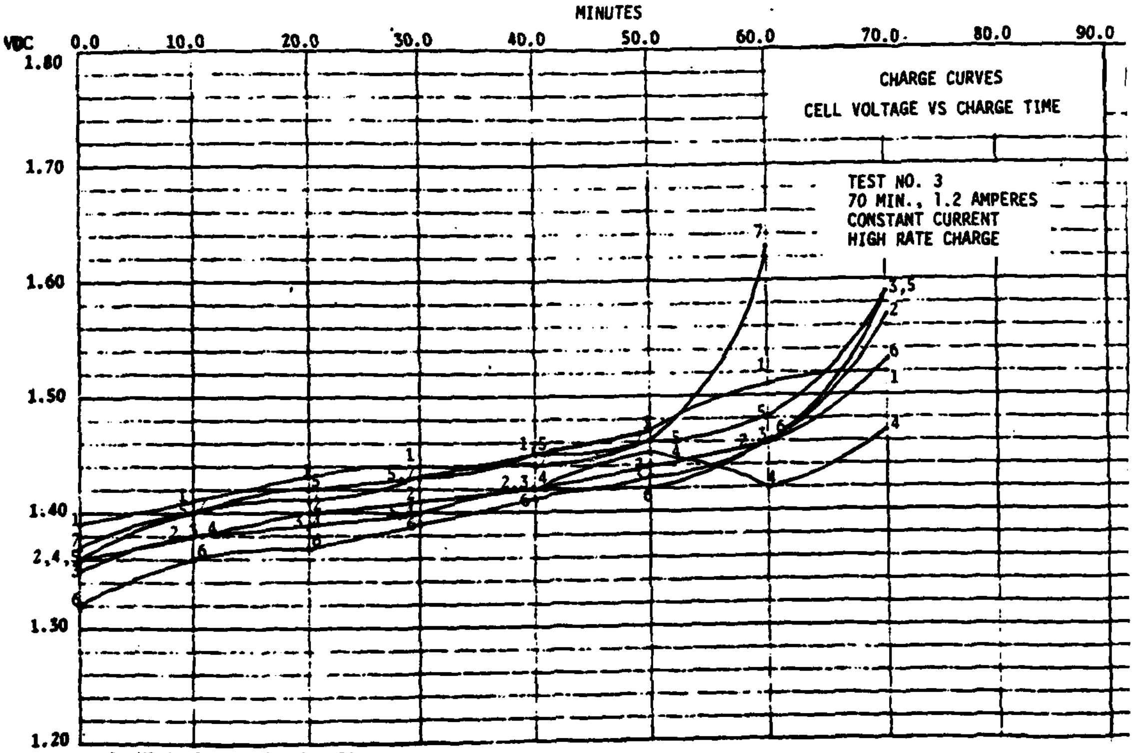
OUTPUT CAPACITY RESULTS

CELL TESTING SUB C

TEST NO./DESCRIPTION	AMPERE HOURS OUT MAR 2 1	SAFT B 2	SAFT L 3	GE 4	PAN 5	SANYO 6	GOULD 7	HIT 8	GE 9	DISCHARGE RATE (AMPS)
TEST 61 Charged for 12 hours 40 minutes 20% duty cycle positive pulse, 5 Hz, 200 Ma, and 2% negative pulse	1.28	0.79	0.98	1.04	1.38	1.24	1.24	0.97		1.2
TEST 62 Charged for 1 hour, 20% duty cycle positive pulse, 5 Hz, 1.5 amperes, and 2% negative pulse	1.26	0.78	0.96	1.02	1.24	1.26	1.24	1.00	1.02	1.2
TEST 63 Charged for 22 minutes at 4A., 50% duty cycle positive pulse and 2% negative pulse, 10 Hz	1.24	0.78	0.83	1.04	0.94	1.24	1.17	0.97	1.01	1.2
TEST 64 Charged for 14 hours at 200 Ma. 50% positive pulse, 20% negative duty cycle pulse, 10 Hz	1.30	0.64	0.98	1.04	1.38	1.28	1.20	1.02	1.02	1.2
TEST 65 Charged for 1 hour at 1.2 Ampere constant current and 3 hours at 150 Ma. constant current	1.28	0.78	1.02	1.07	1.34	1.28	1.20	1.02	1.02	1.2
TEST 66 Charged for 36 hours at 100 Ma. constant current	1.28	0.73	0.95	1.04	1.33	1.27	1.25	0.95	1.02	1.2

APPENDIX C - CELL CHARGE GRAPHS





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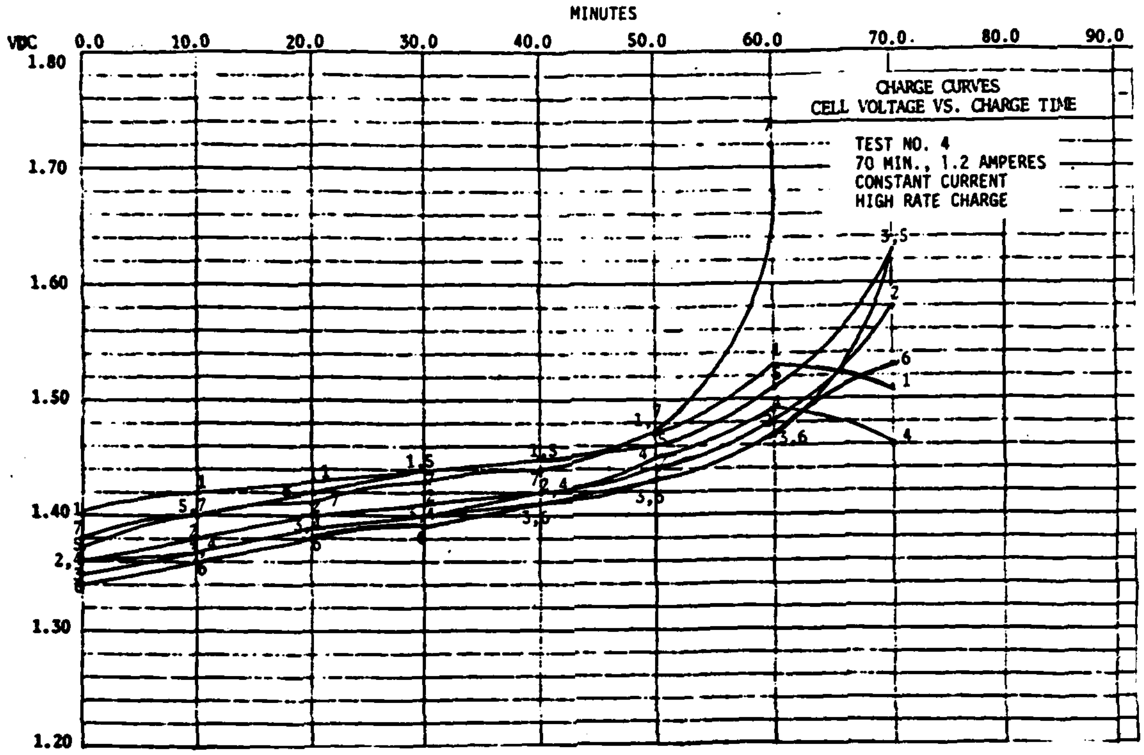
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD


MINUTES
VDC
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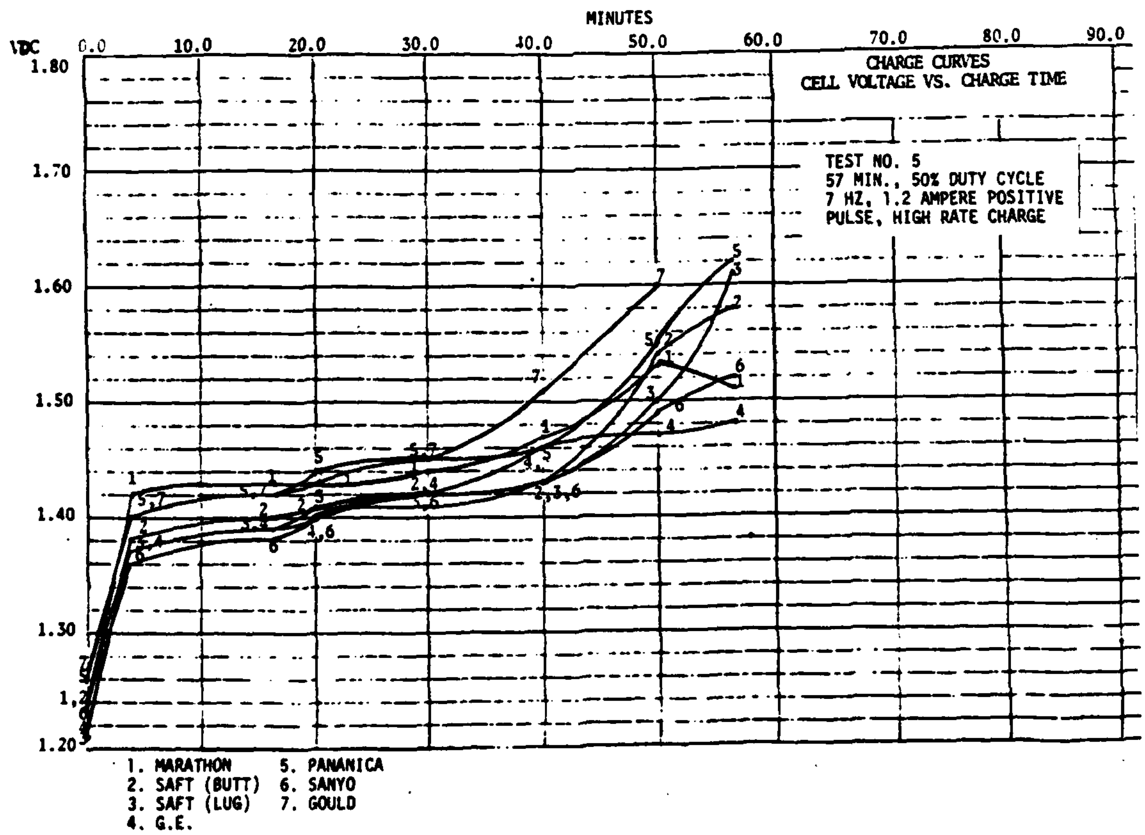
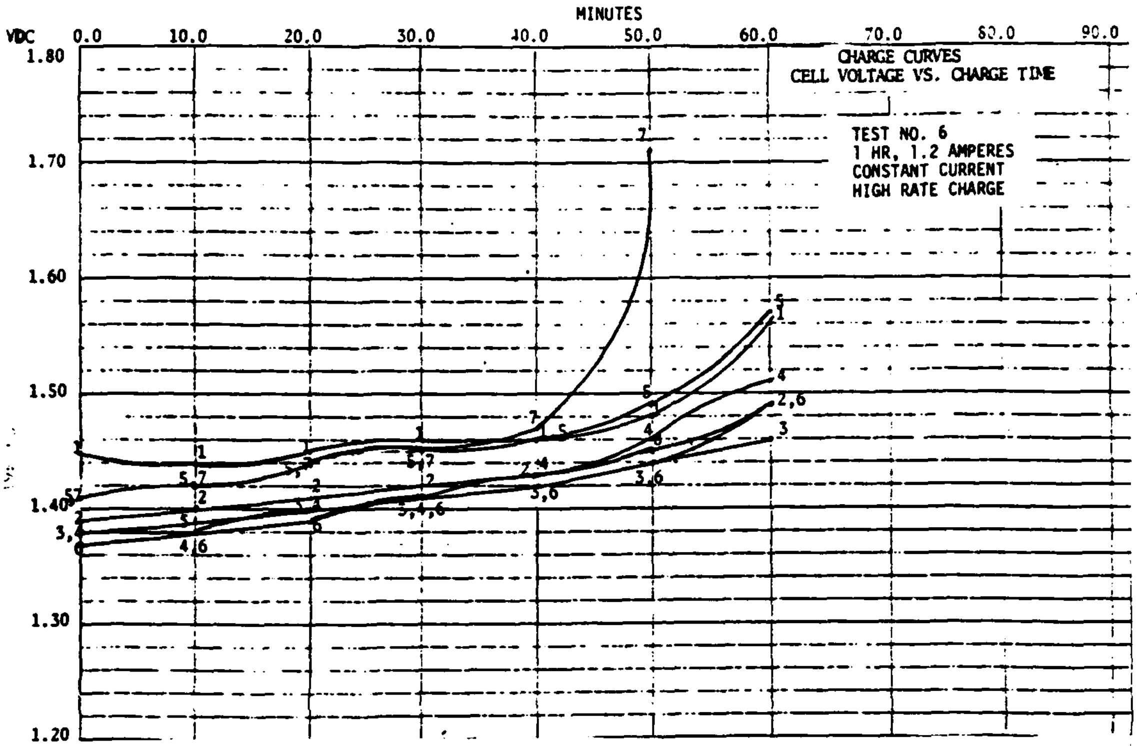
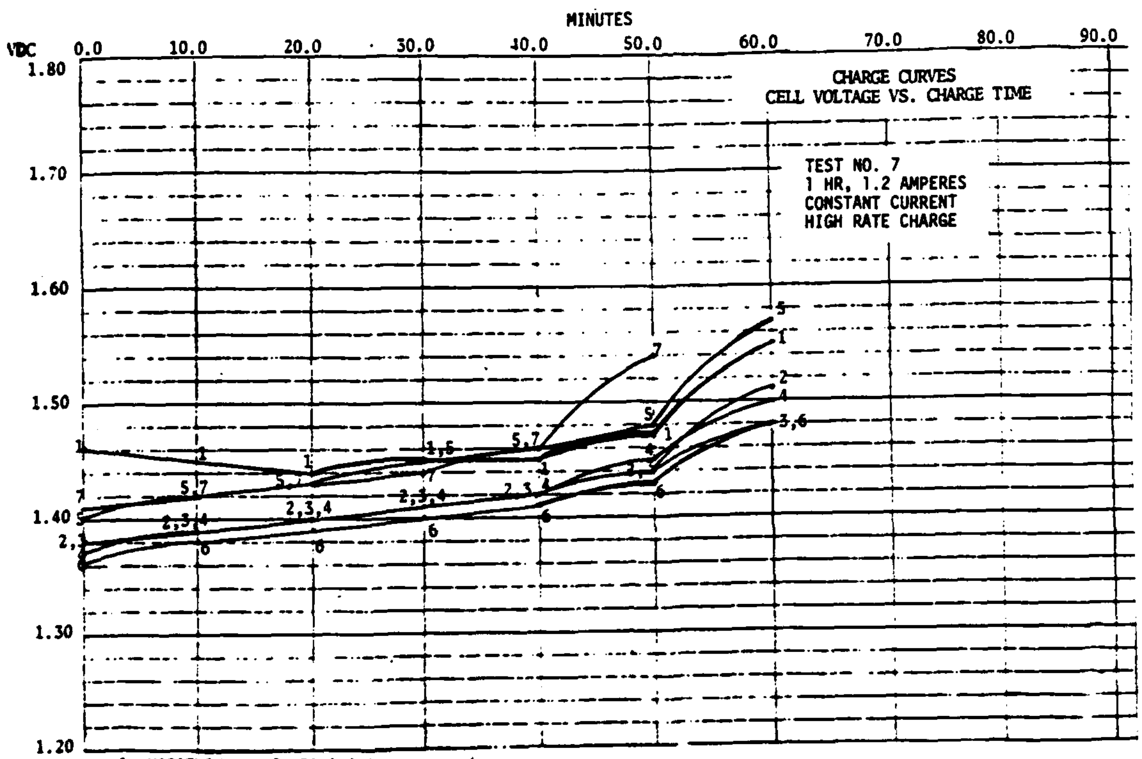
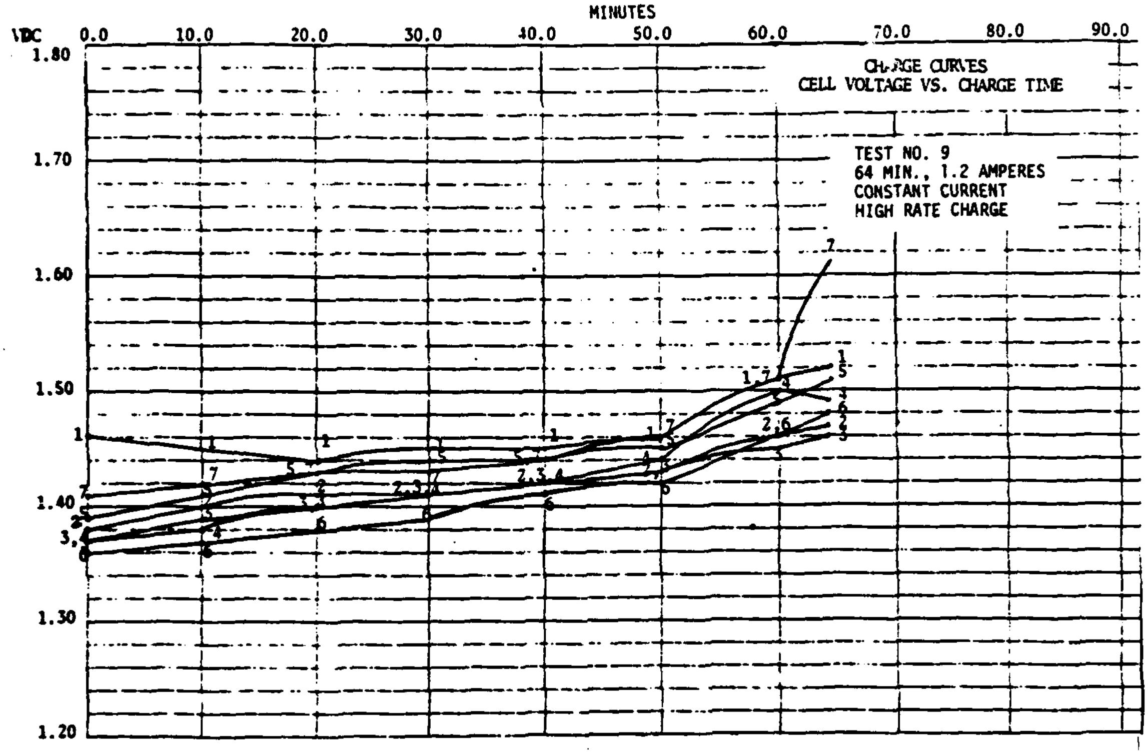
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
1.80
1.70
1.60
1.50
1.40
1.30
1.20
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 4
70 MIN., 1.2 AMPERES
CONSTANT CURRENT
HIGH RATE CHARGE

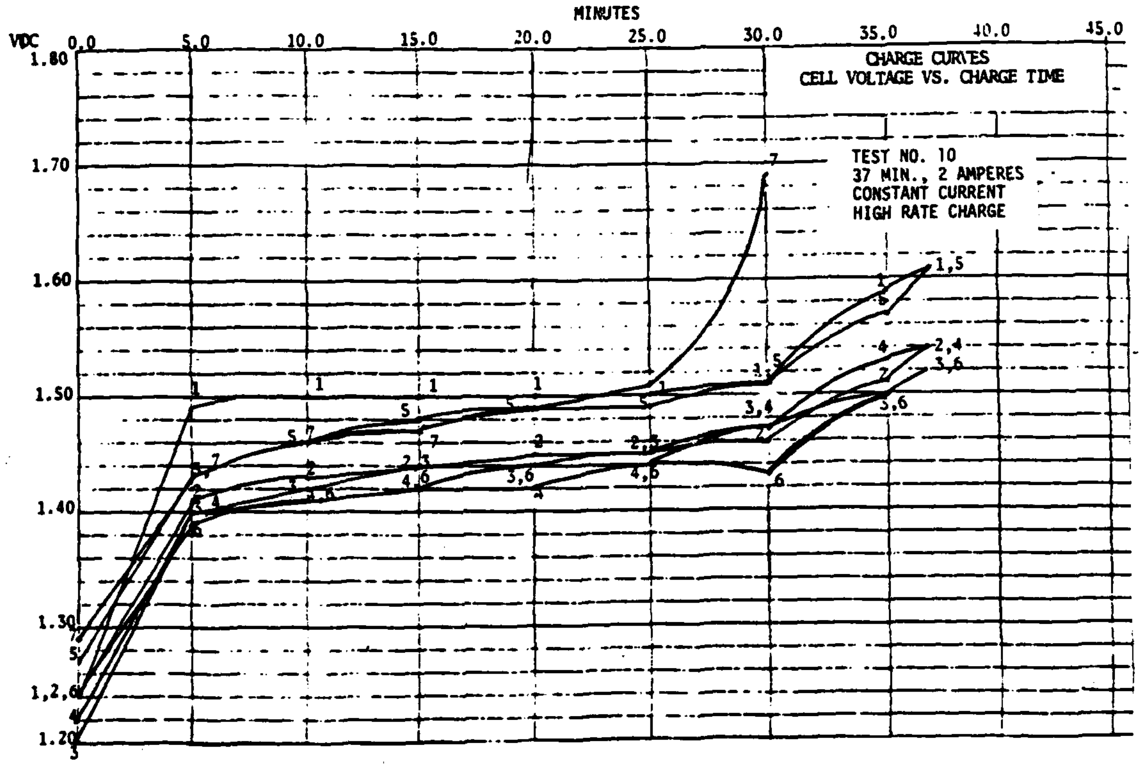

MINUTES
VDC
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
1.80
1.70
1.60
1.50
1.40
1.30
1.20
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 5
57 MIN., 50% DUTY CYCLE
7 HZ, 1.2 AMPERE POSITIVE
PULSE, HIGH RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



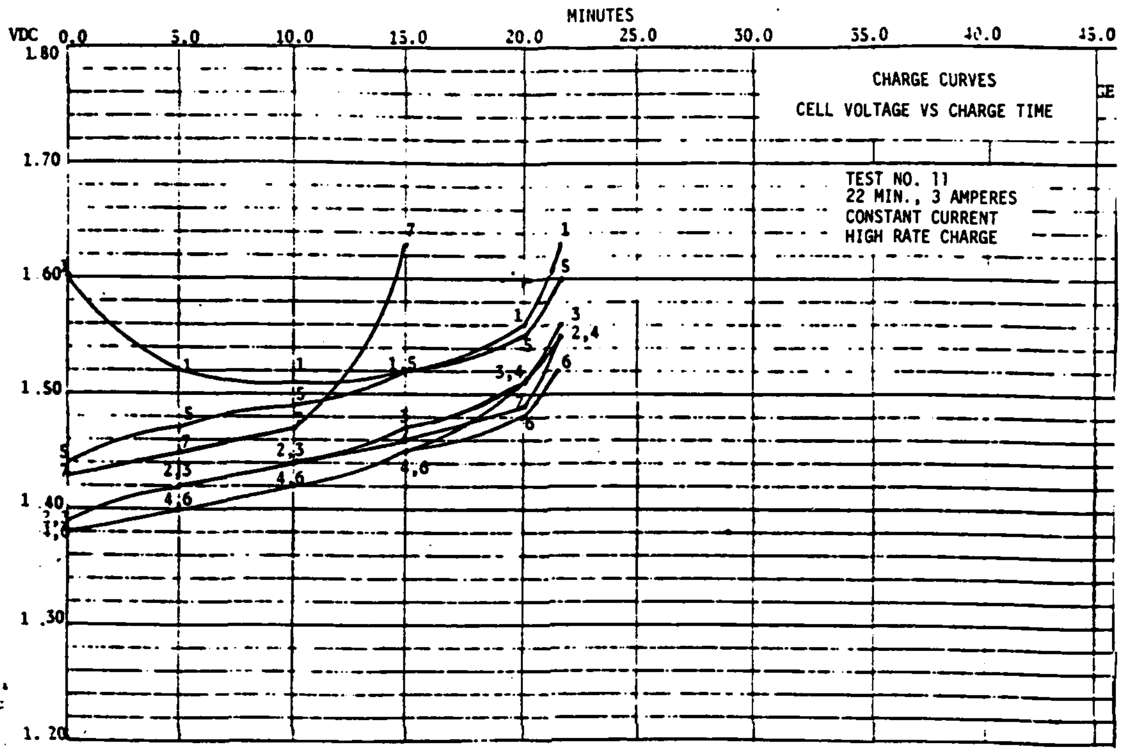


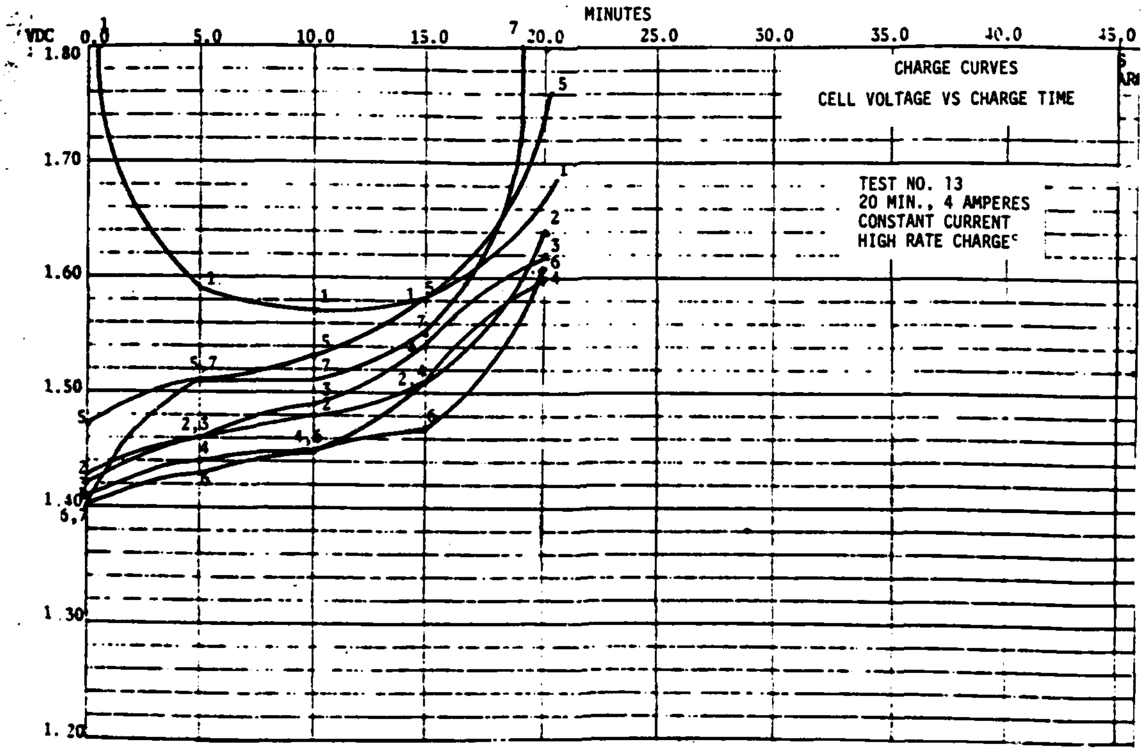
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD





1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E.





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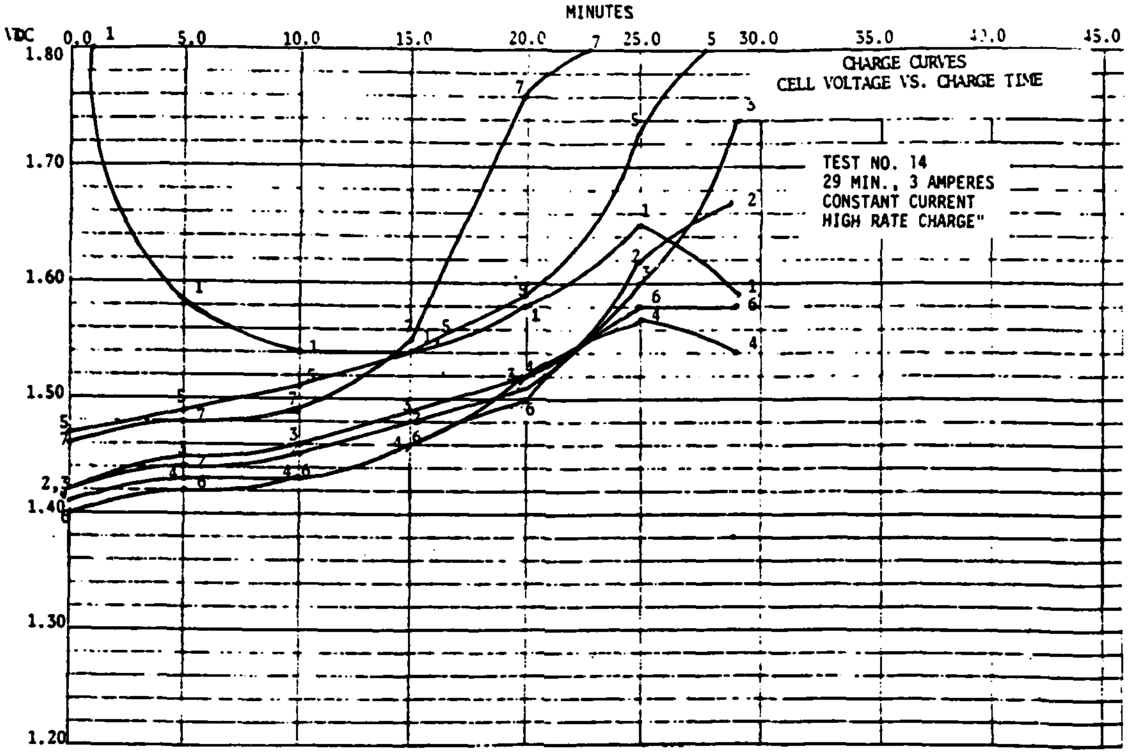
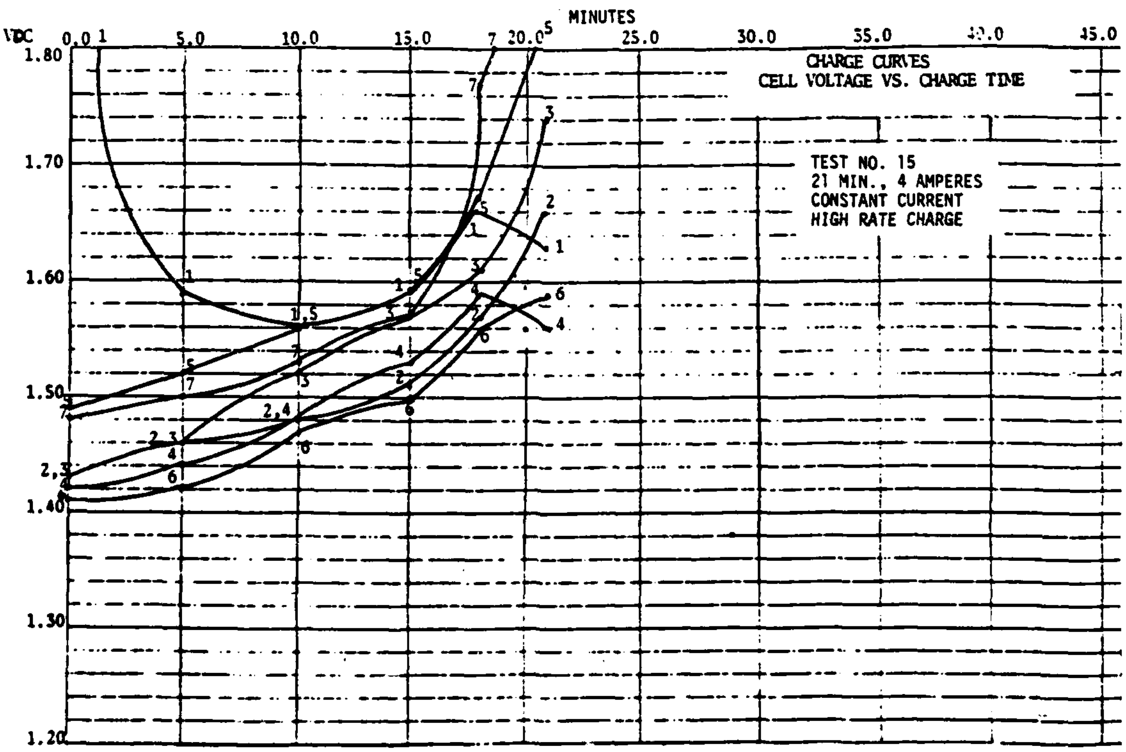
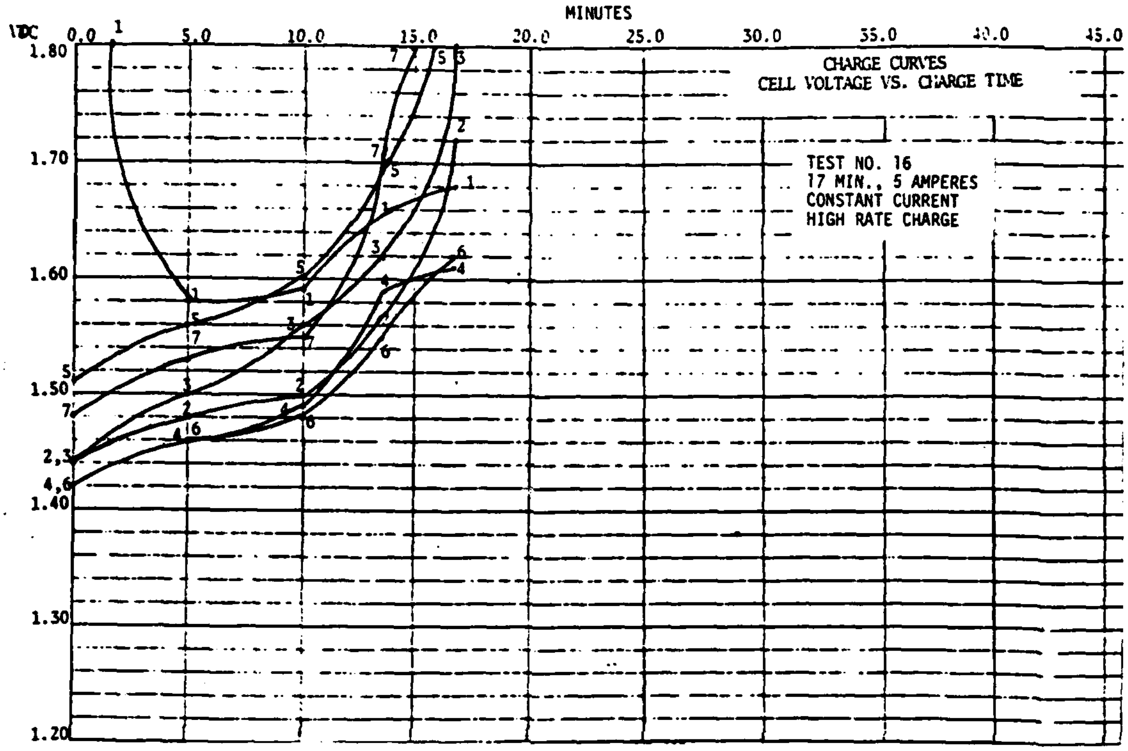
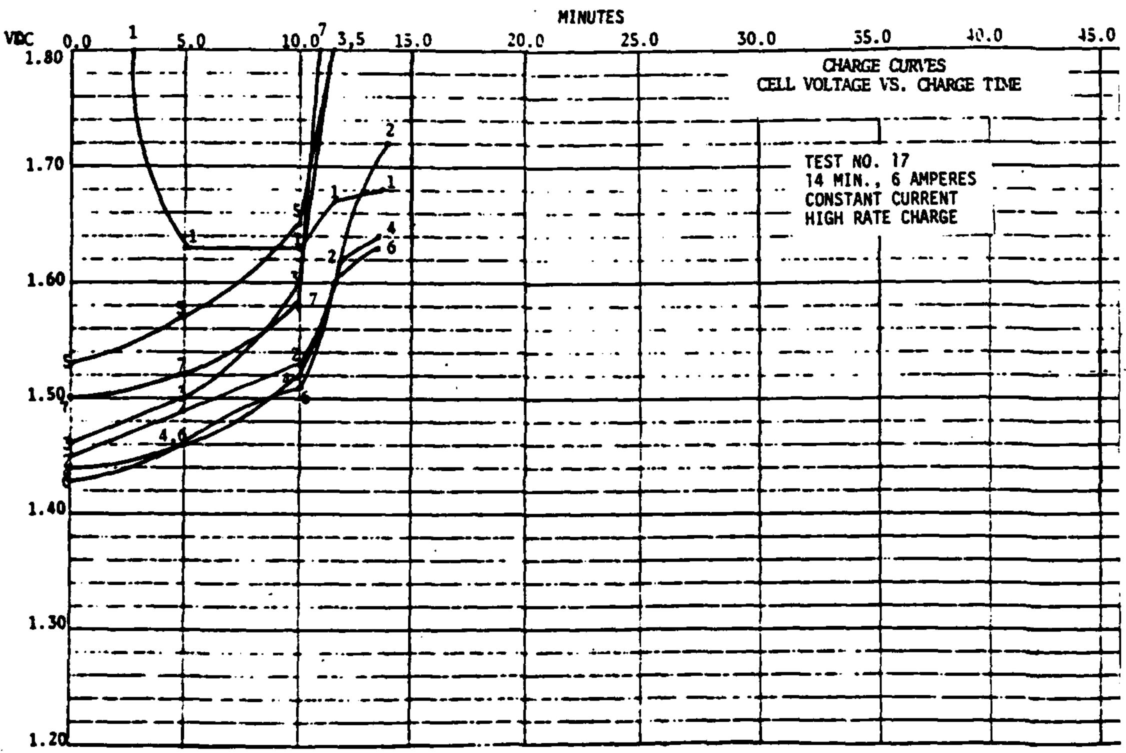
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



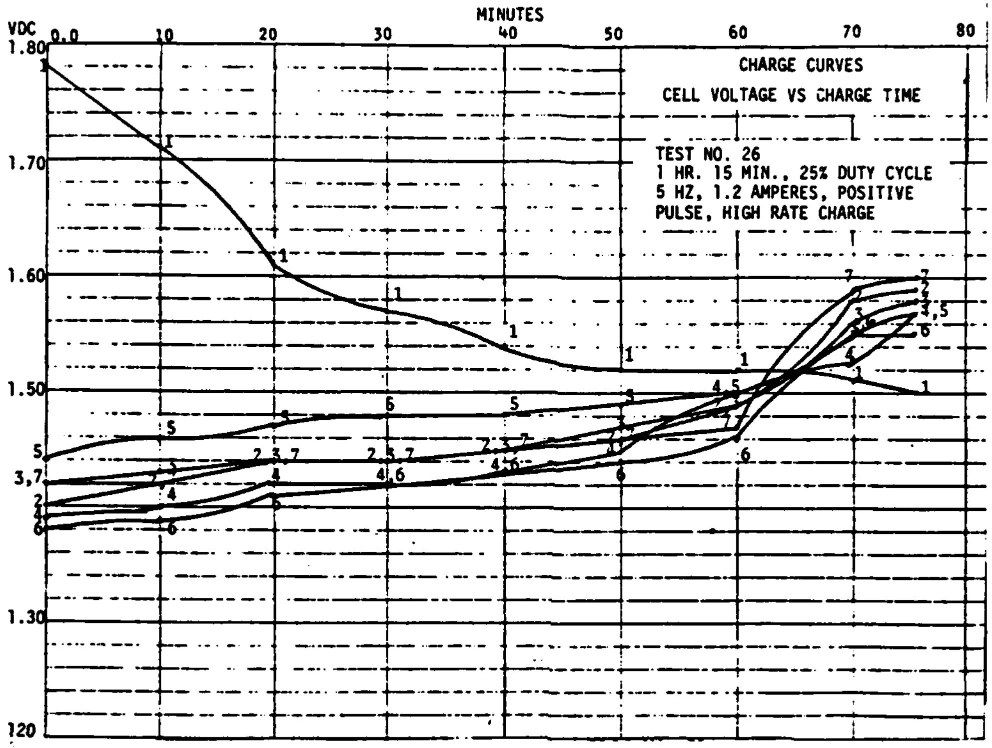


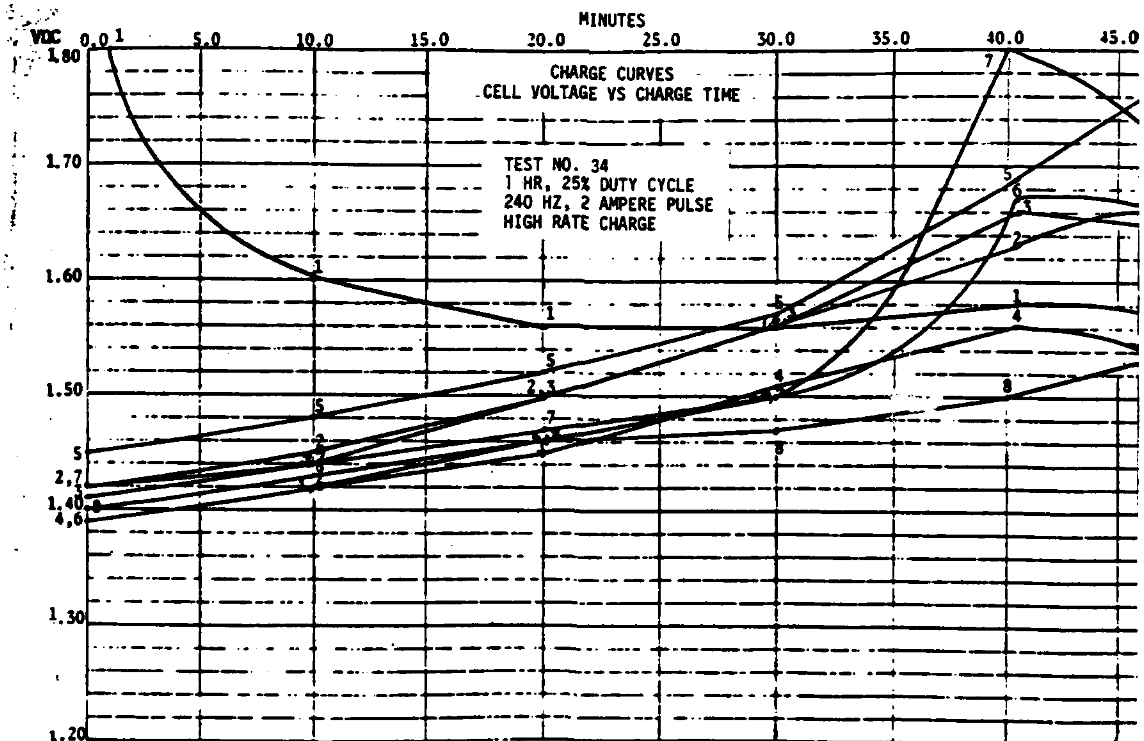
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



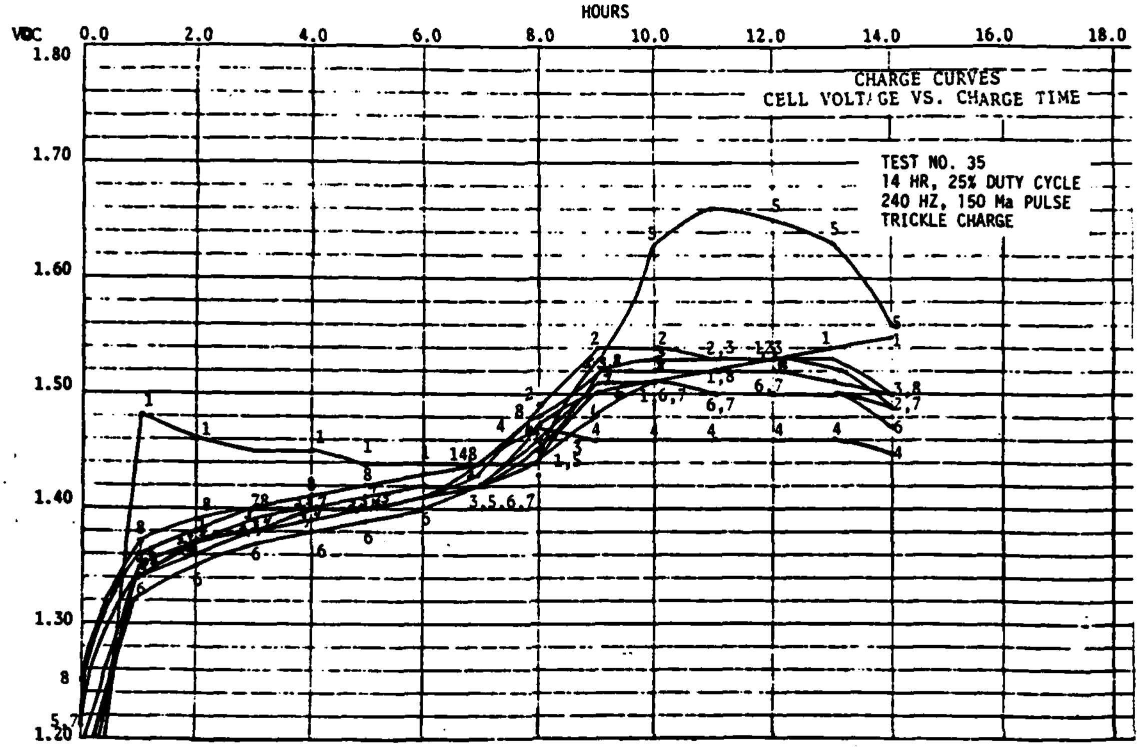


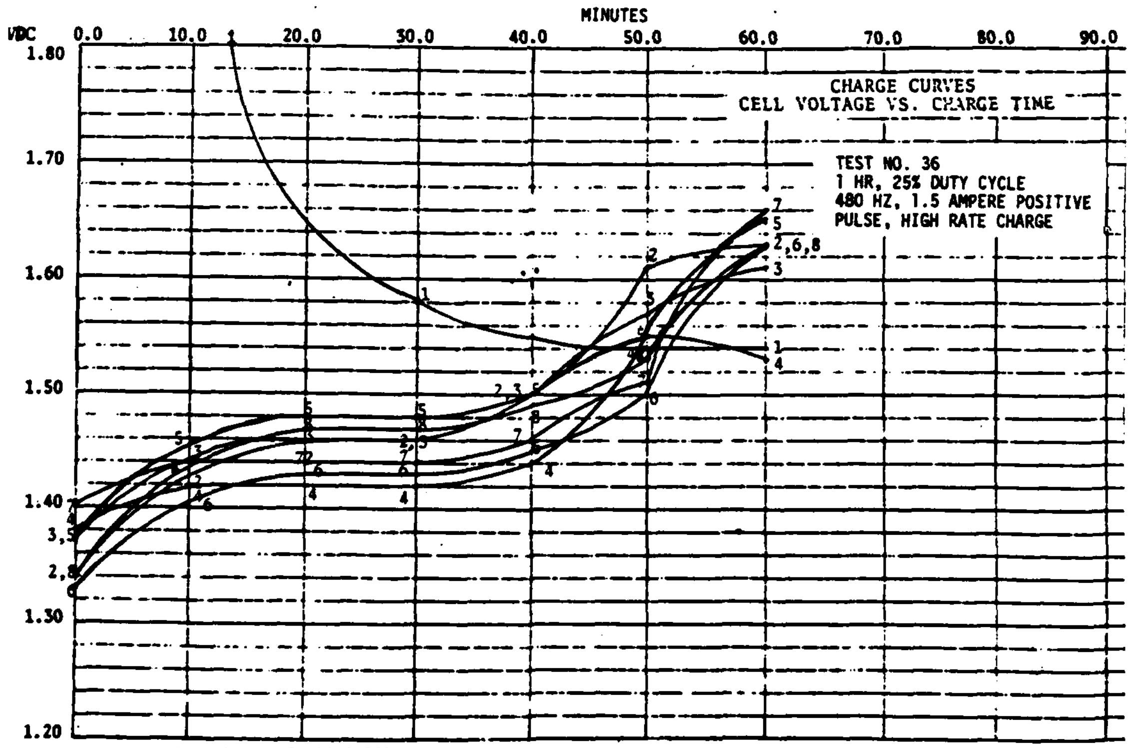
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



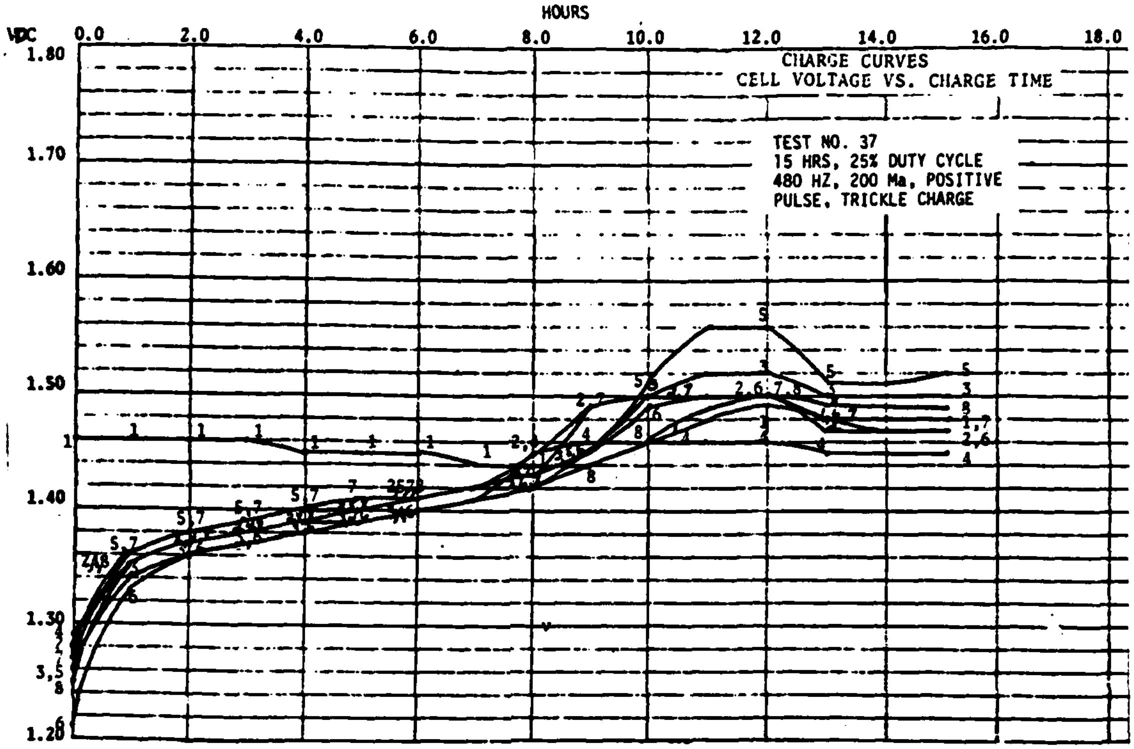


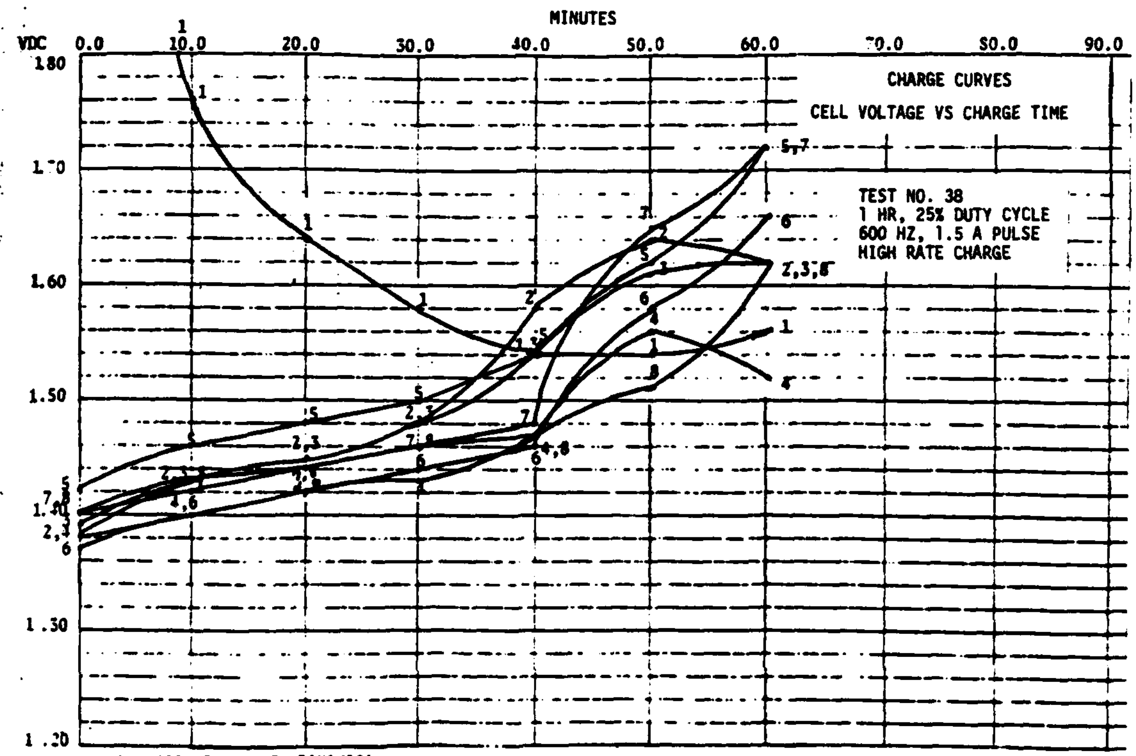
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



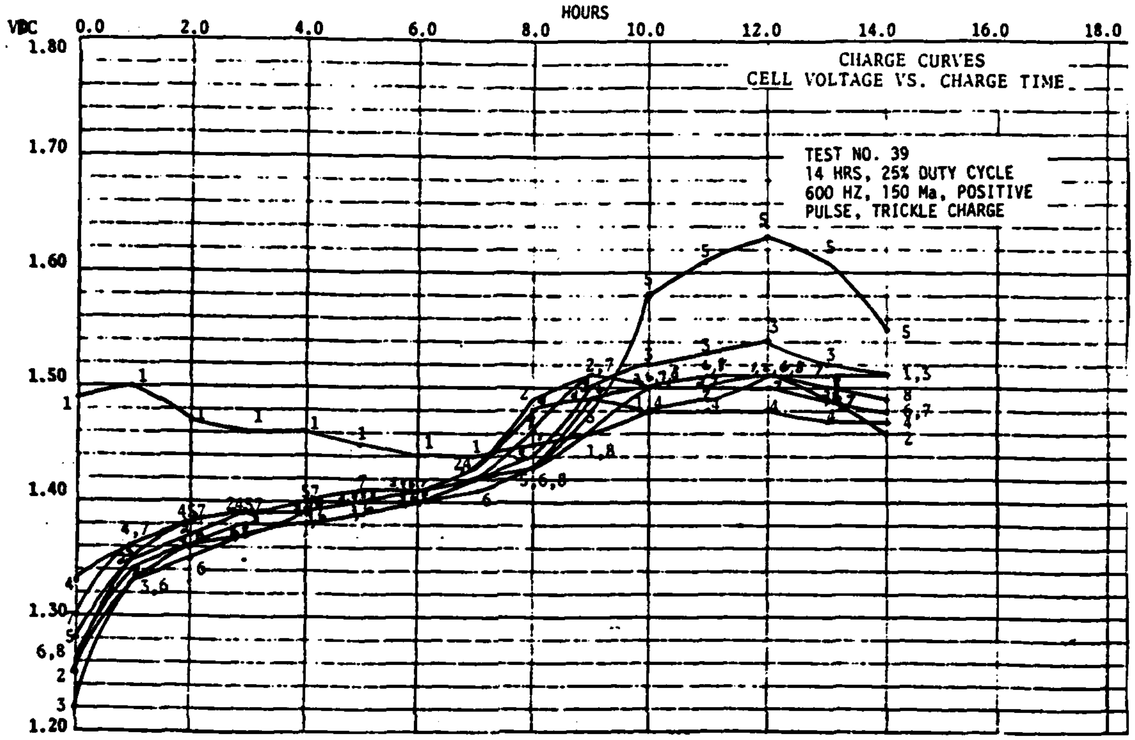


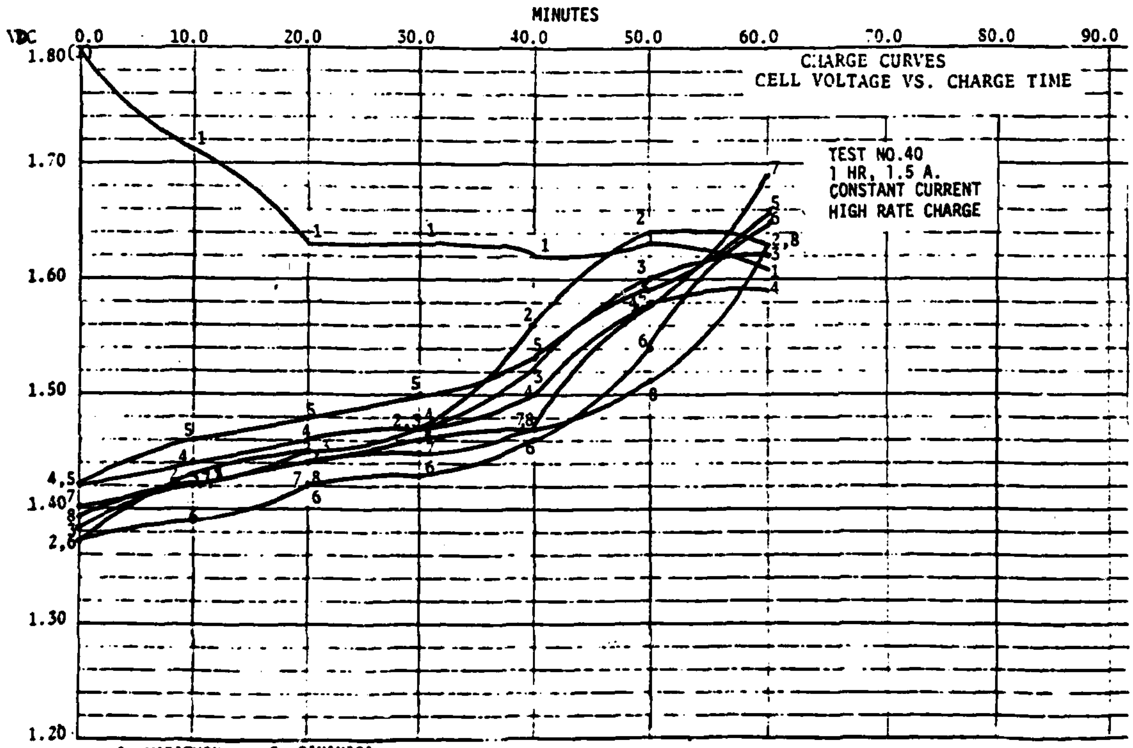
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



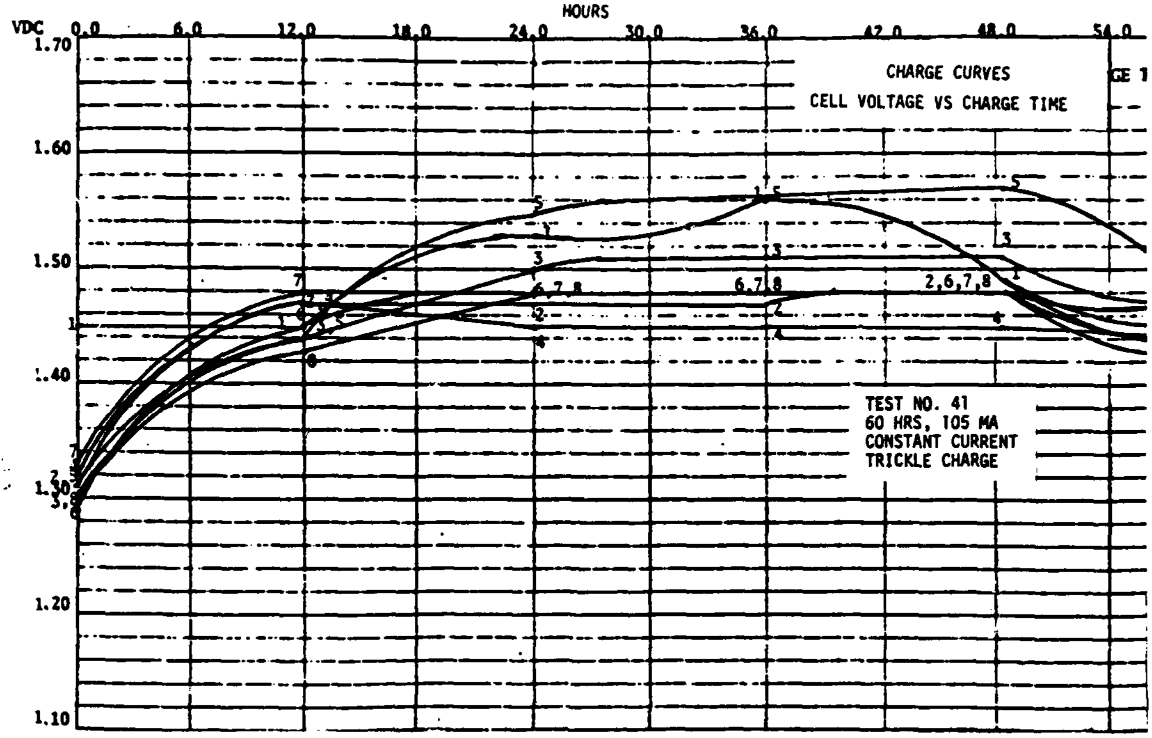


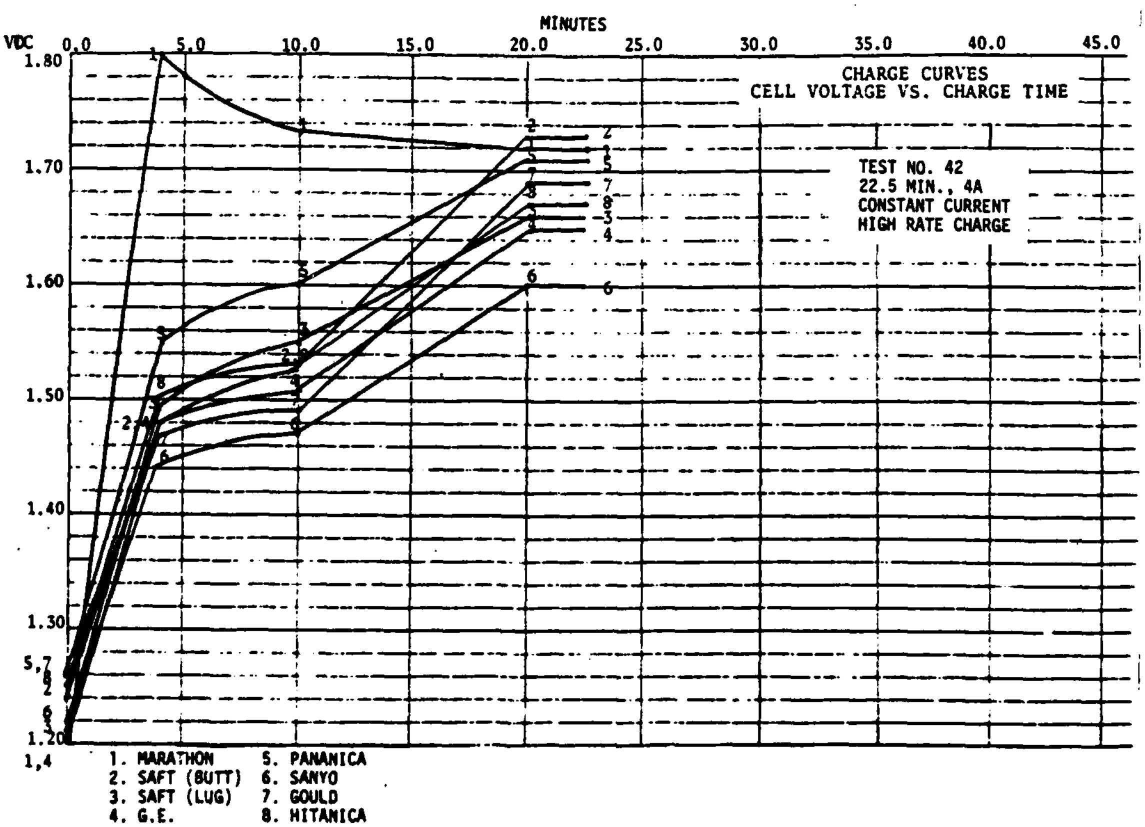
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

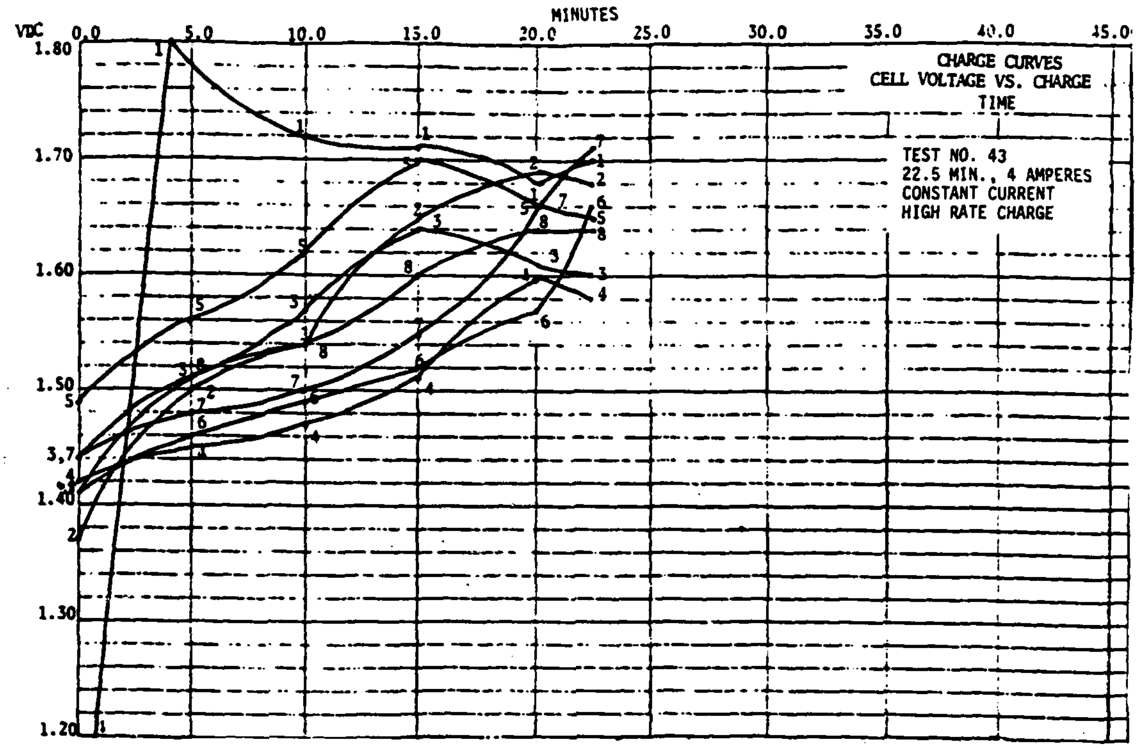


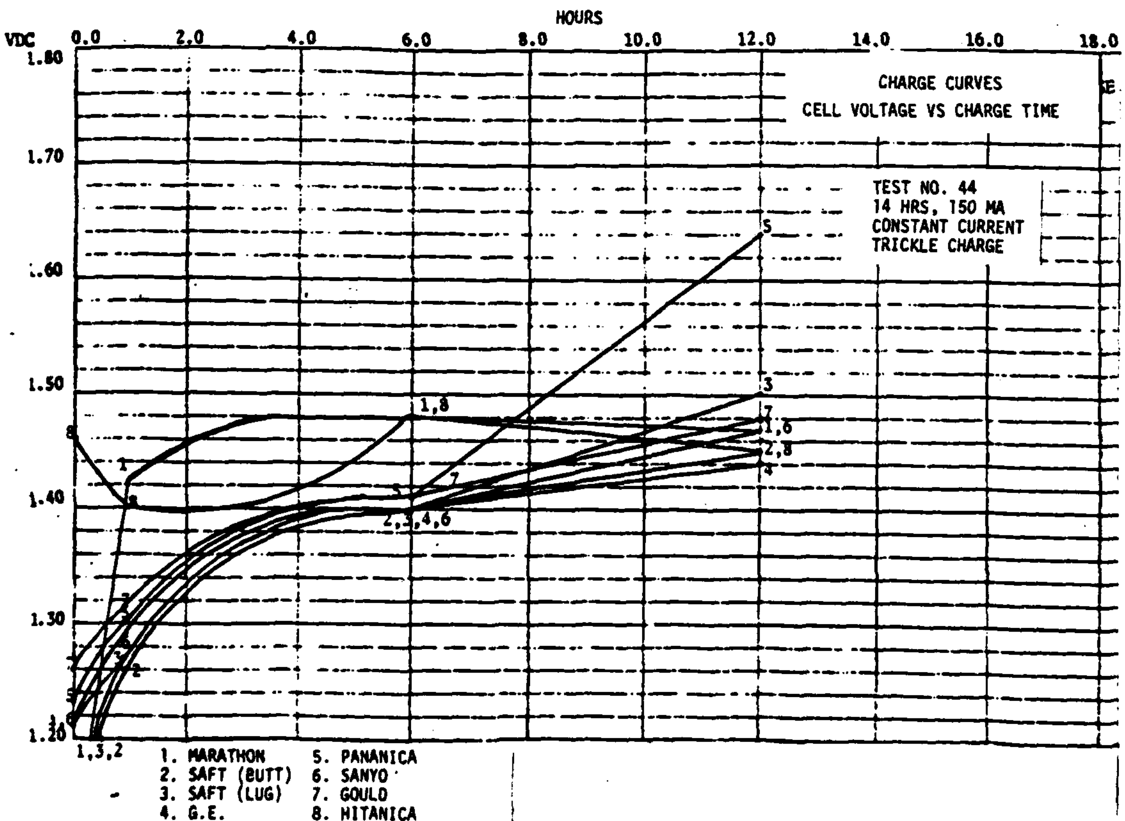


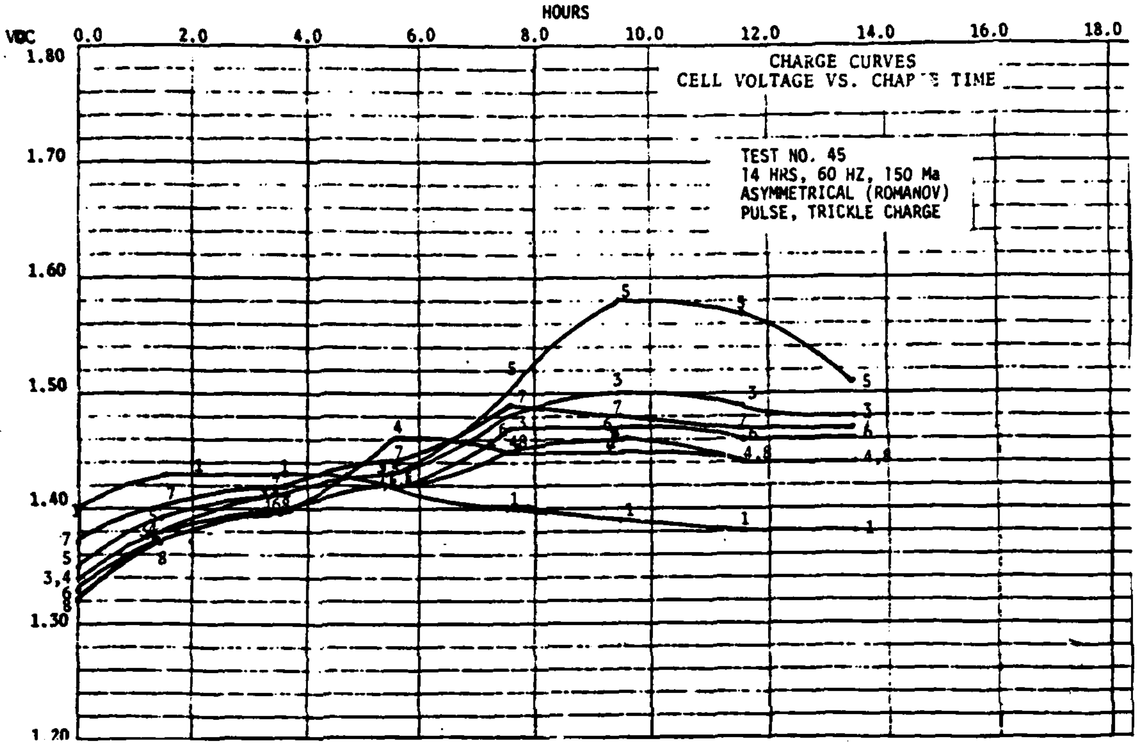
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

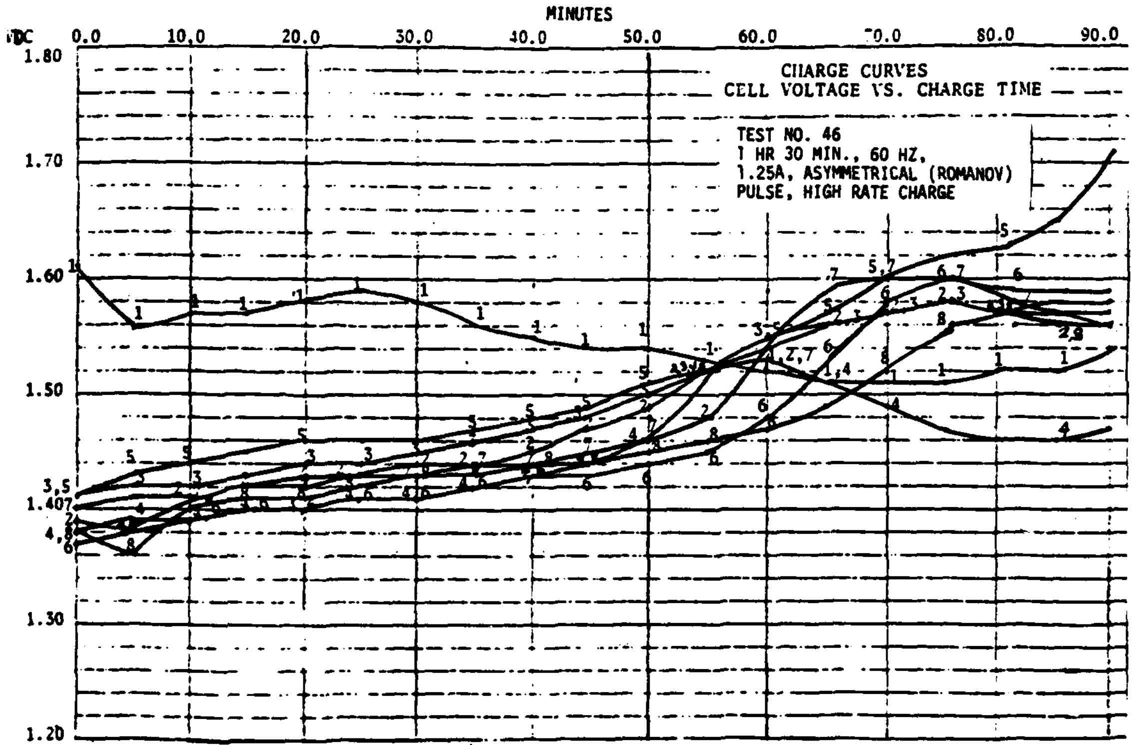

HOURS
VDC
0.0
6.0
12.0
18.0
24.0
30.0
36.0
42.0
48.0
54.0
1.70
1.60
1.50
1.40
1.30
1.20
1.10
CHARGE CURVES
CELL VOLTAGE VS CHARGE TIME
TEST NO. 41
60 HRS, 105 MA
CONSTANT CURRENT
TRICKLE CHARGE


MINUTES
VDC
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
1.80
1.70
1.60
1.50
1.40
1.30
1.20
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 42
22.5 MIN., 4A
CONSTANT CURRENT
HIGH RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

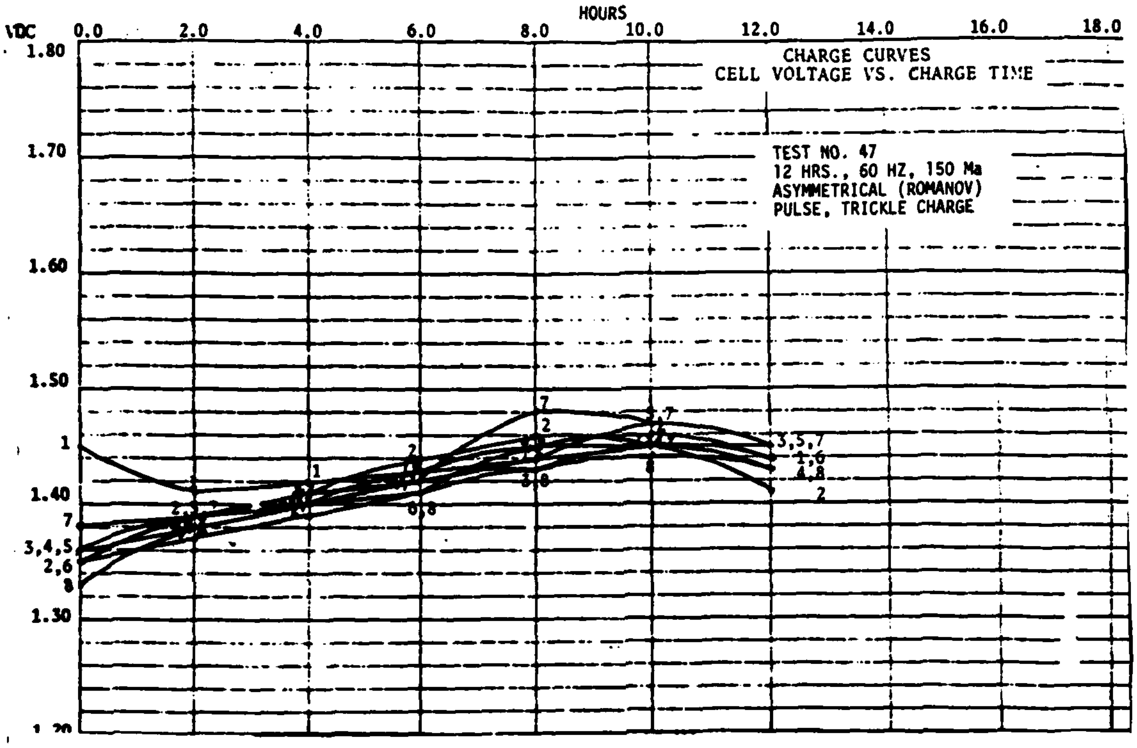

MINUTES
VDC
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 43
22.5 MIN., 4 AMPERES
CONSTANT CURRENT
HIGH RATE CHARGE

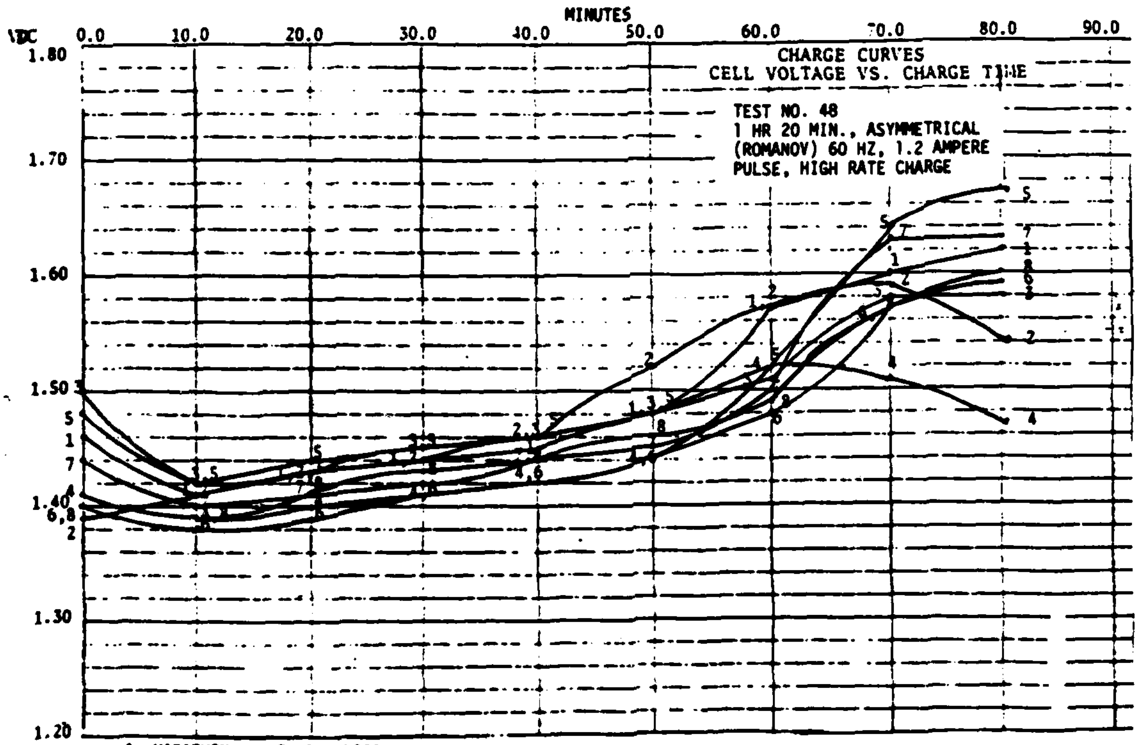

HOURS
VDC
CHARGE CURVES
CELL VOLTAGE VS CHARGE TIME
TEST NO. 44
14 HRS, 150 MA
CONSTANT CURRENT
TRICKLE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



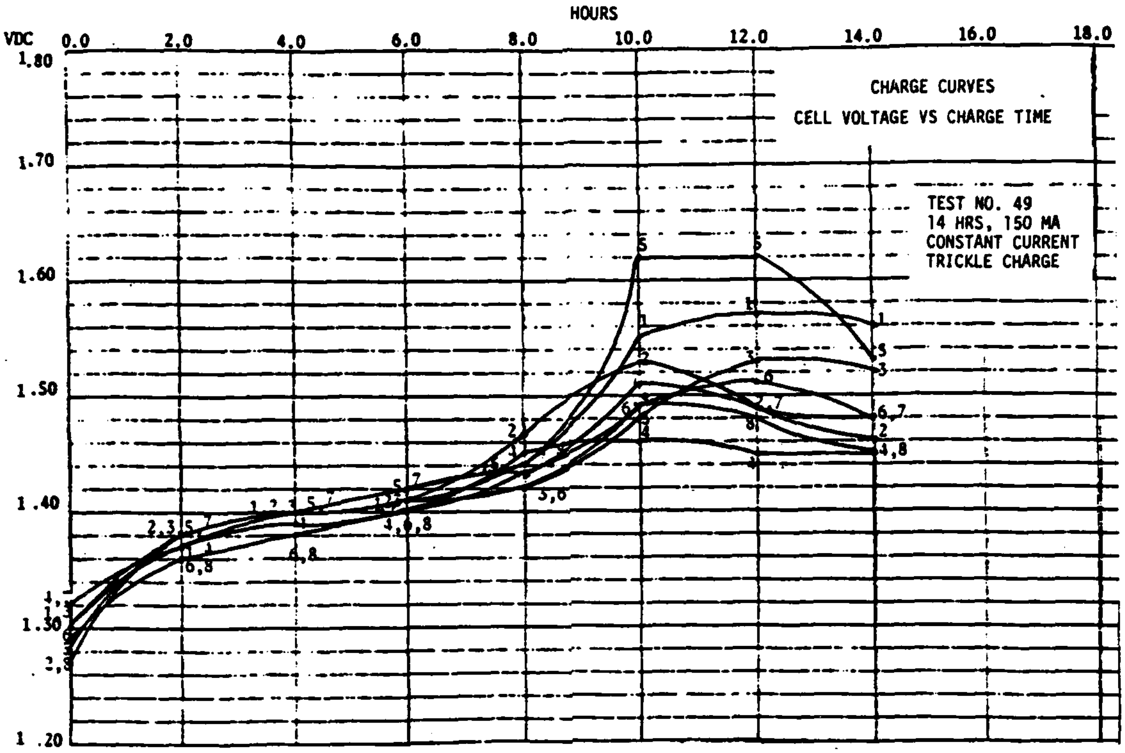


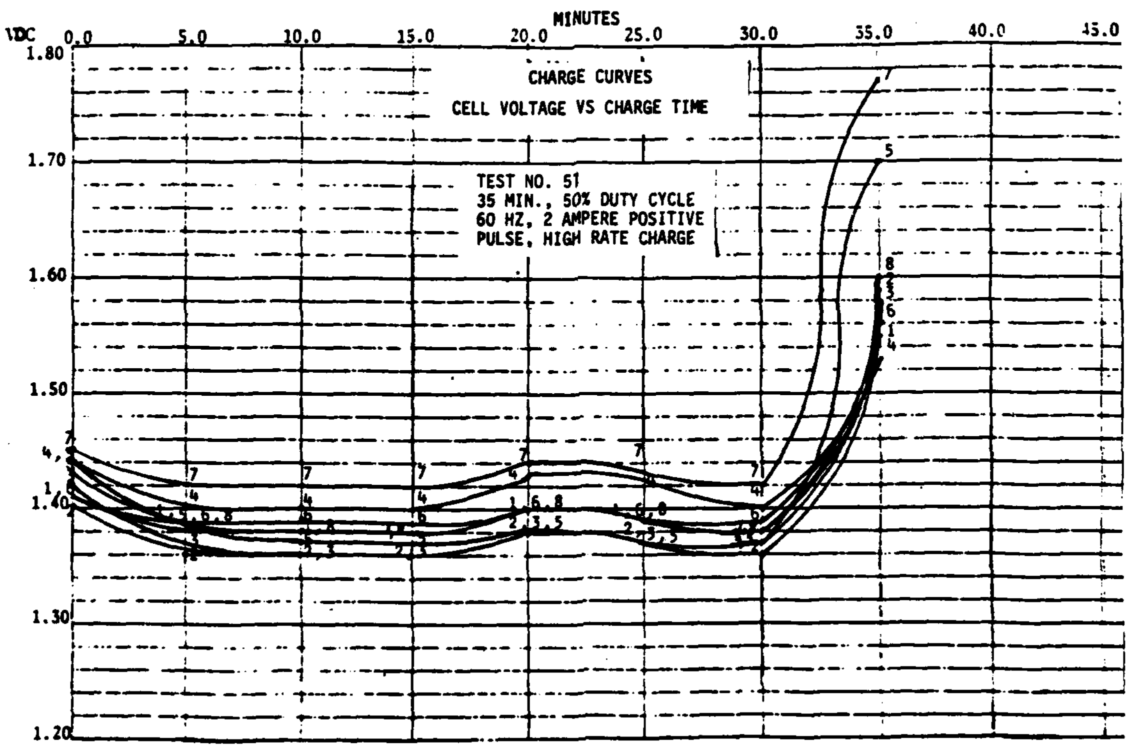
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



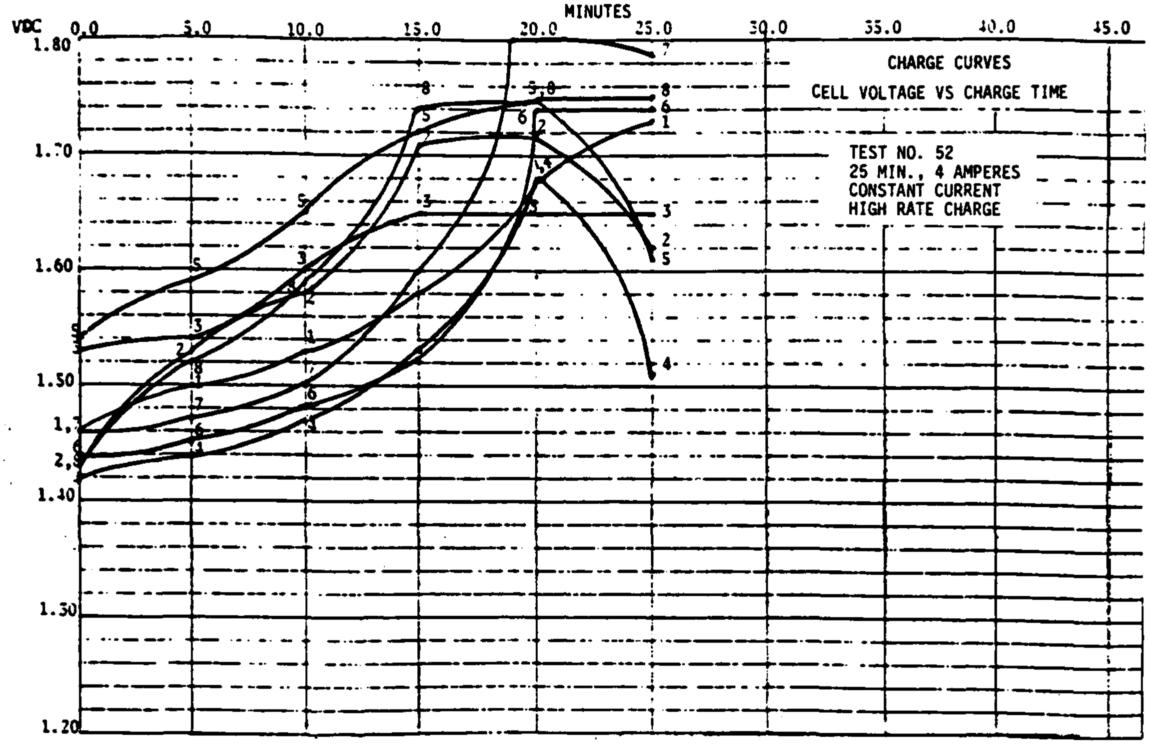


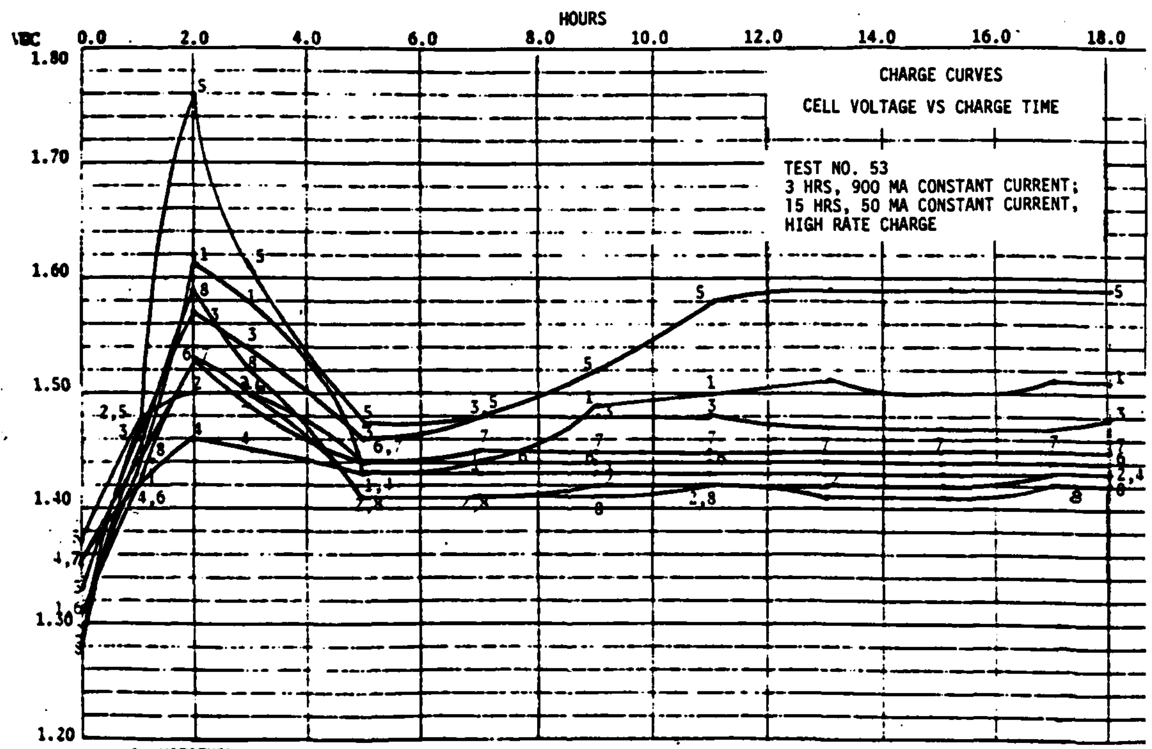
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



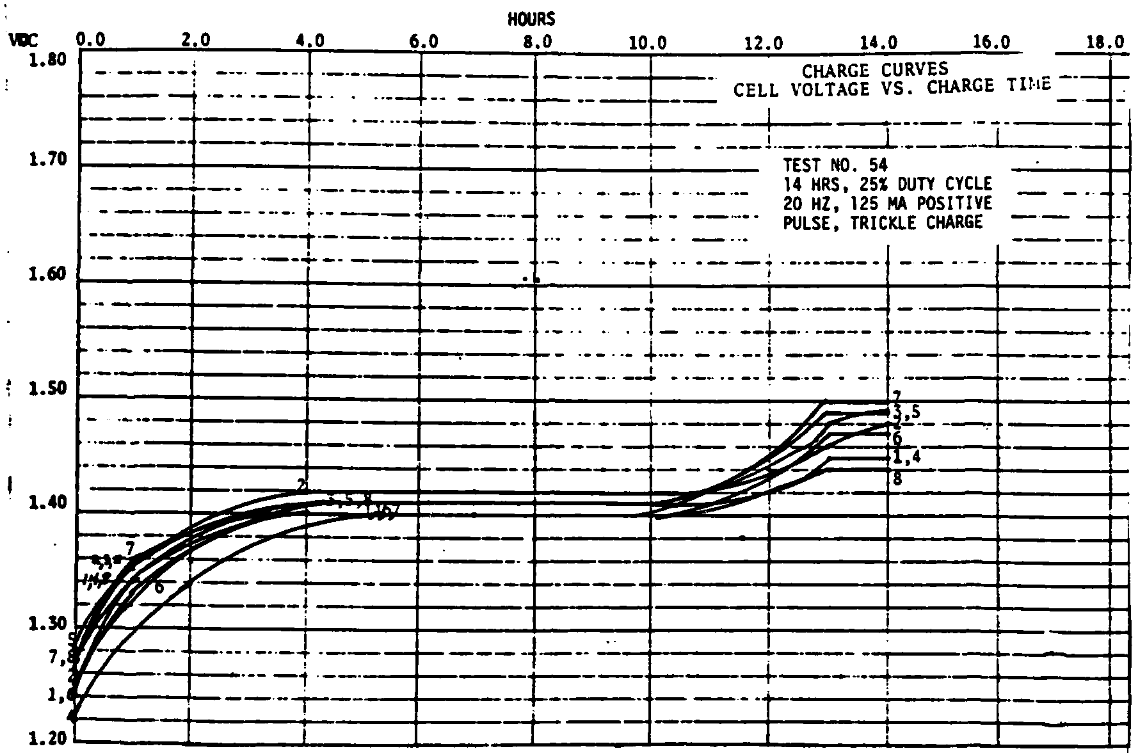


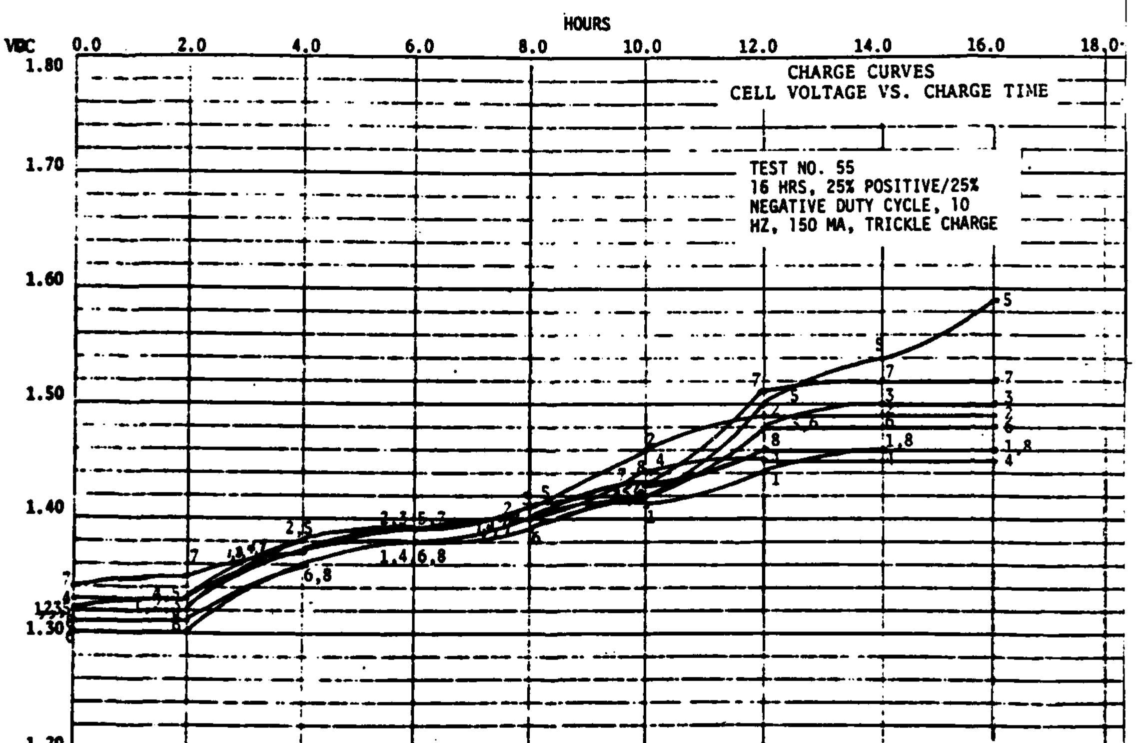
1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E. 8 - HITANICA



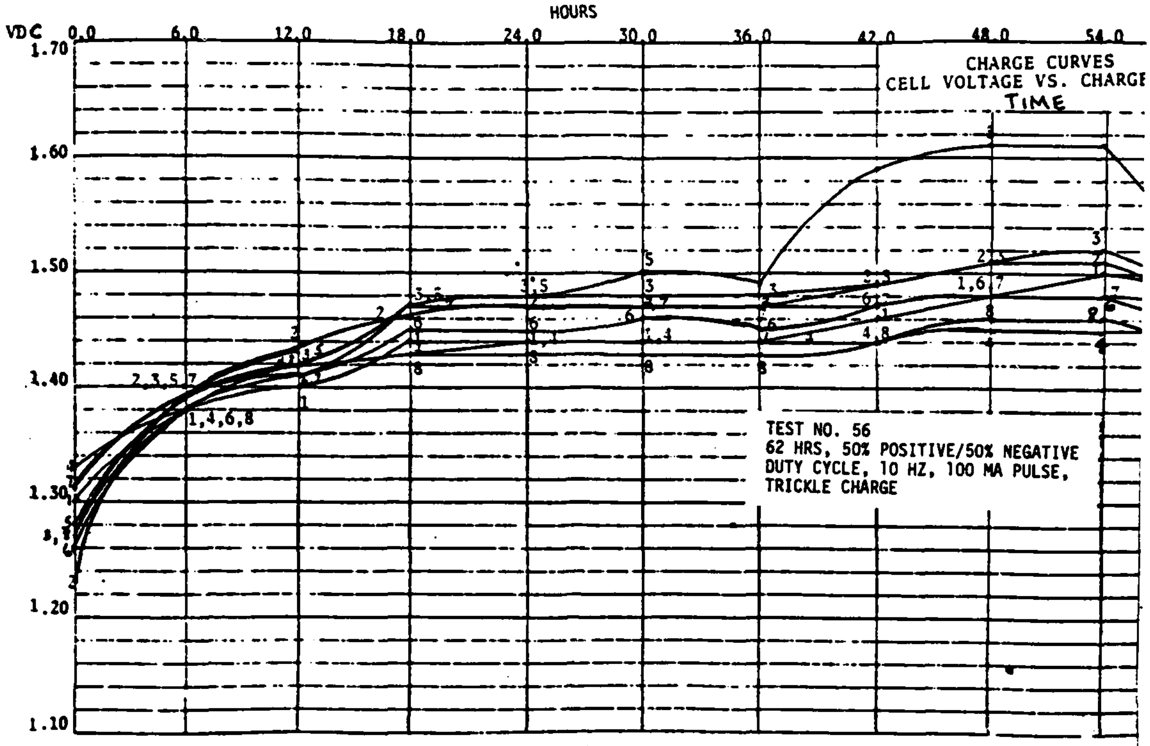


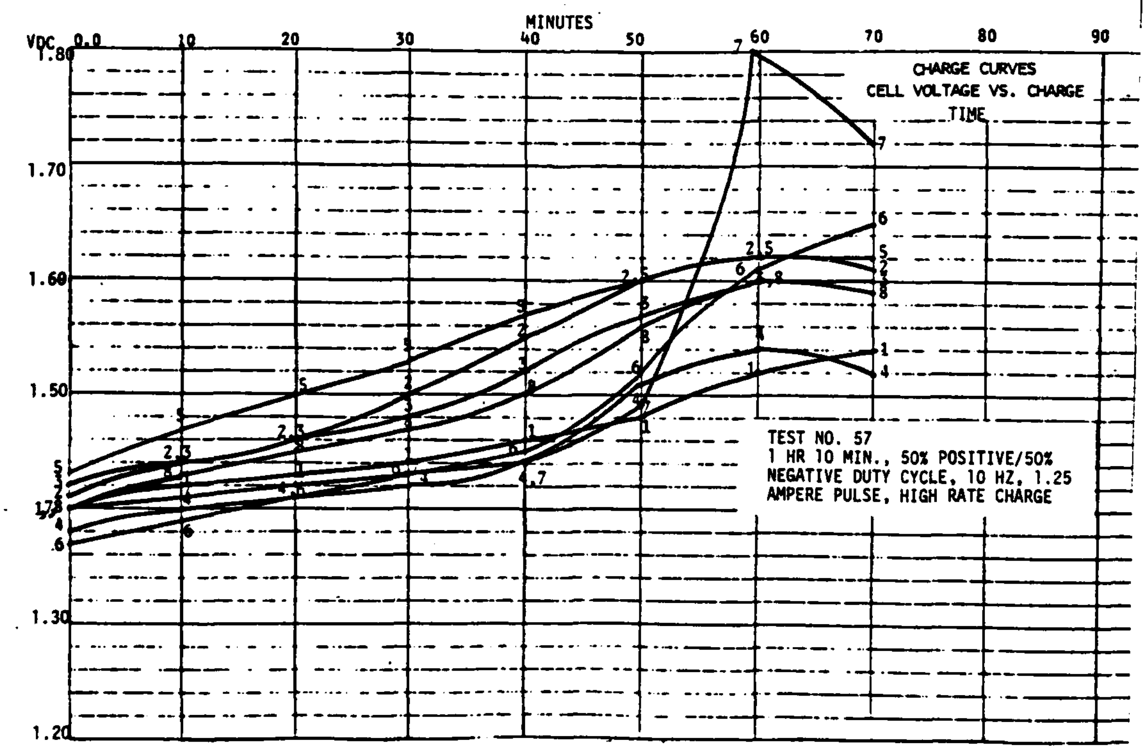
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



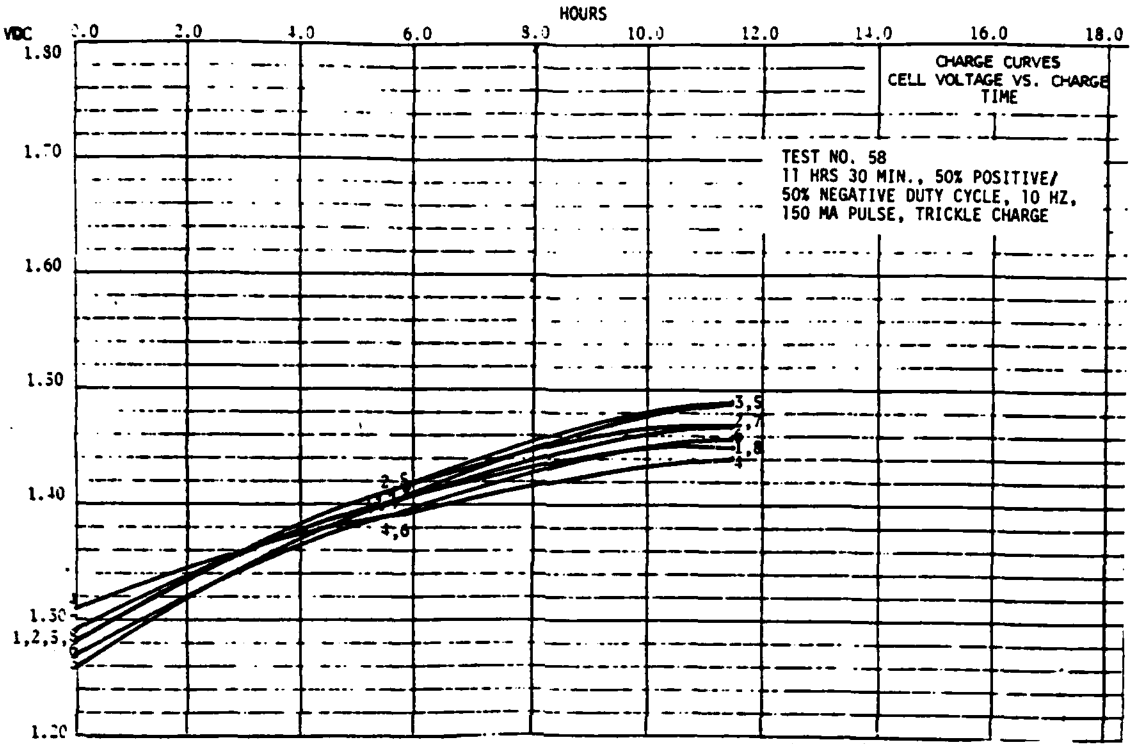


1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD
8 - HITANICA

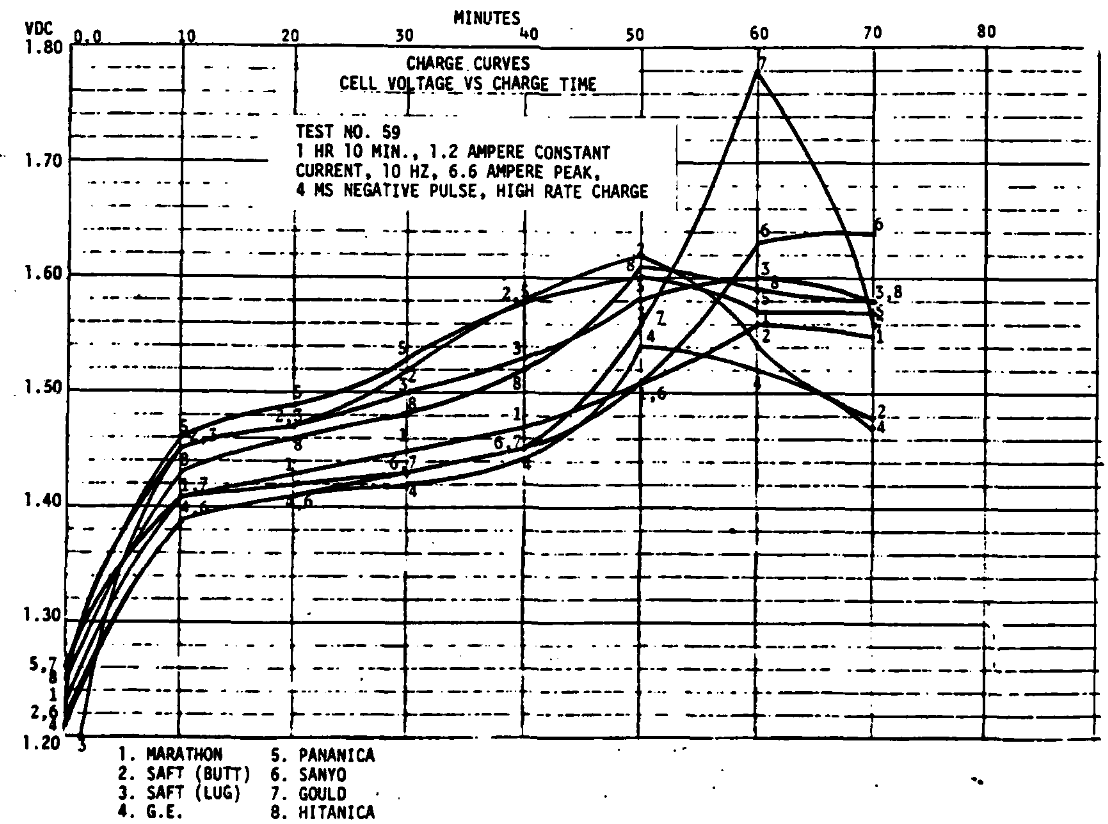




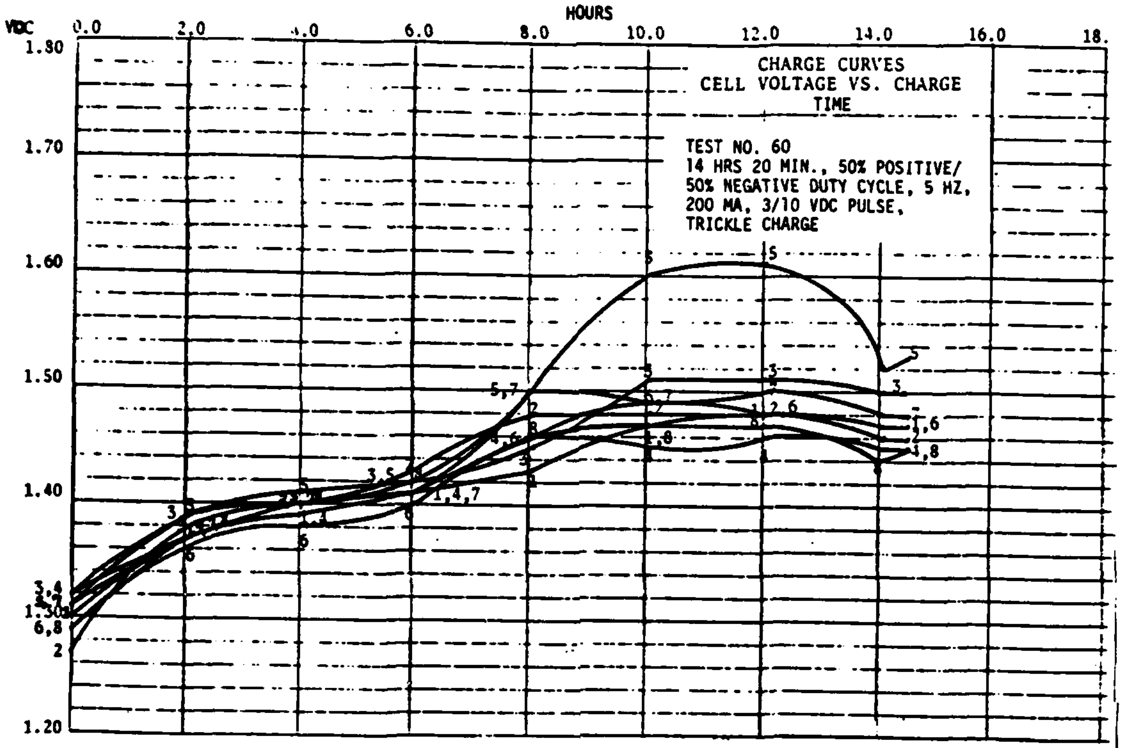
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

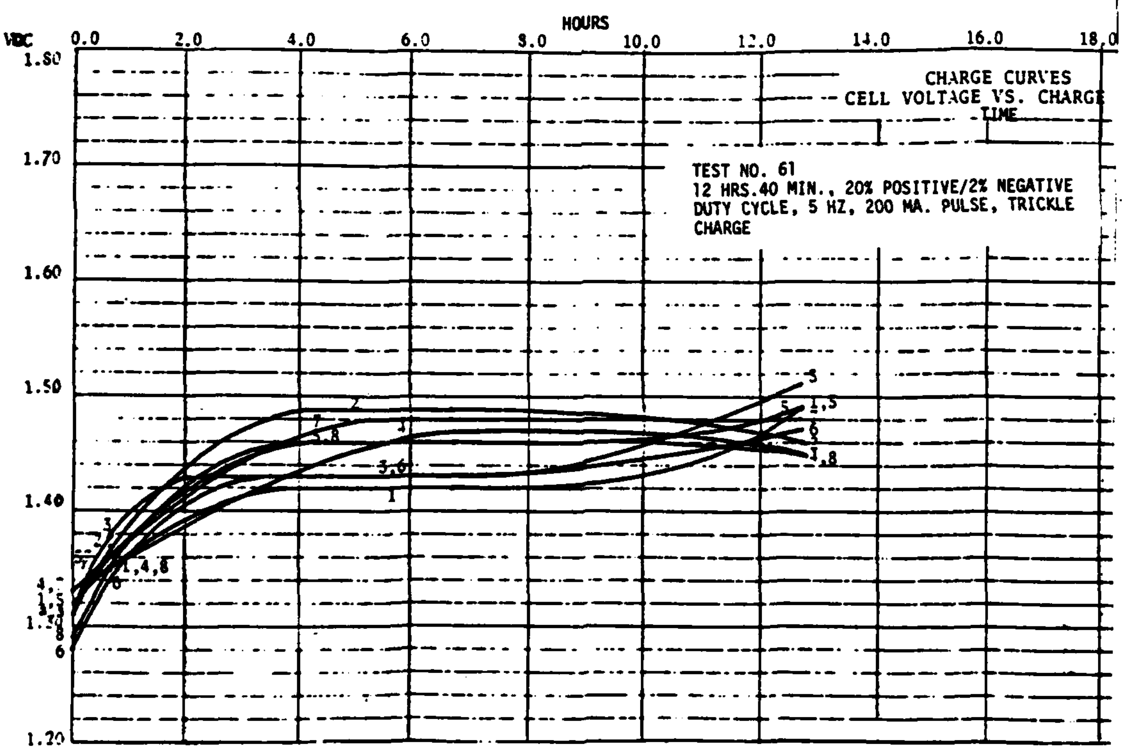


HOURS
VDC
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 58
11 HRS 30 MIN., 50% POSITIVE/
50% NEGATIVE DUTY CYCLE, 10 HZ,
150 MA PULSE, TRICKLE CHARGE

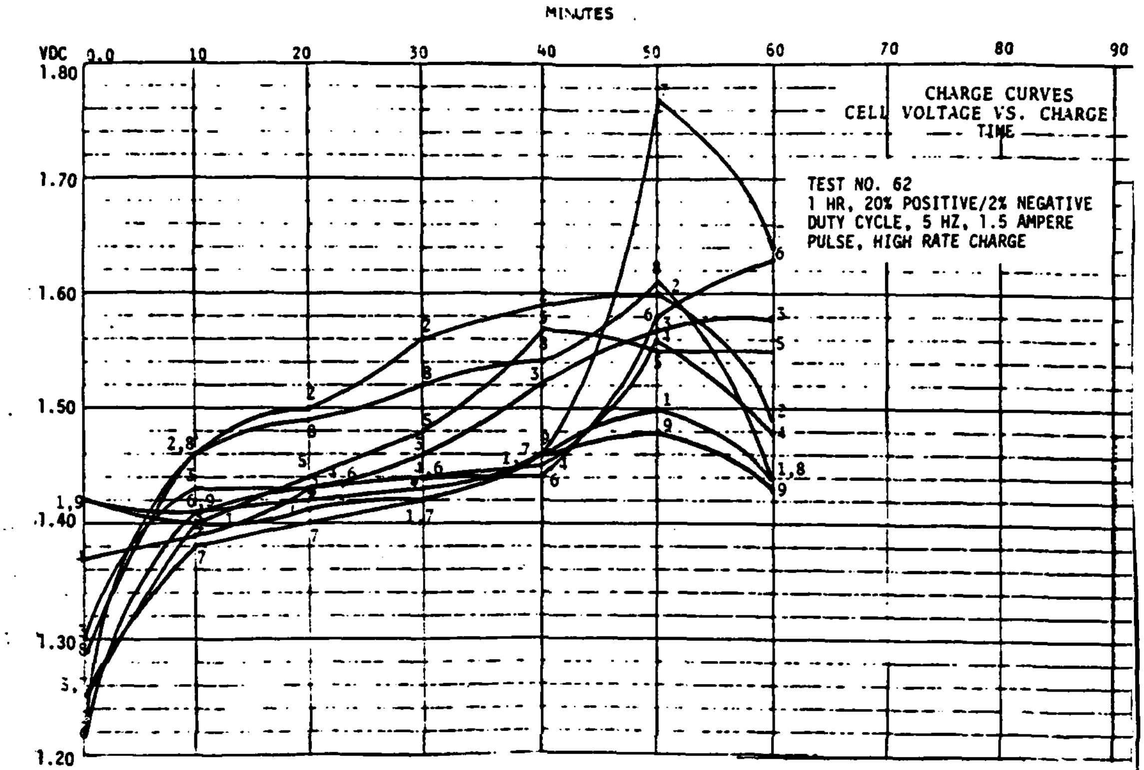


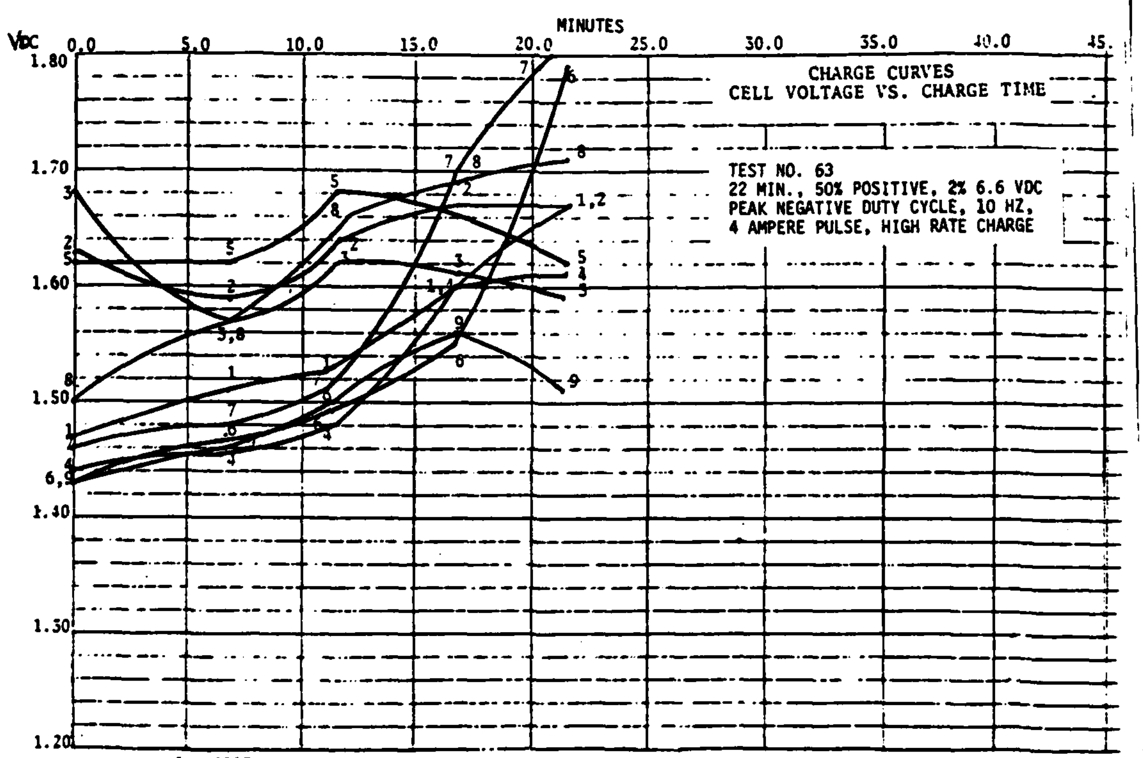
MINUTES
VDC
CHARGE CURVES
CELL VOLTAGE VS CHARGE TIME
TEST NO. 59
1 HR 10 MIN., 1.2 AMPERE CONSTANT
CURRENT, 10 HZ, 6.6 AMPERE PEAK,
4 MS NEGATIVE PULSE, HIGH RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



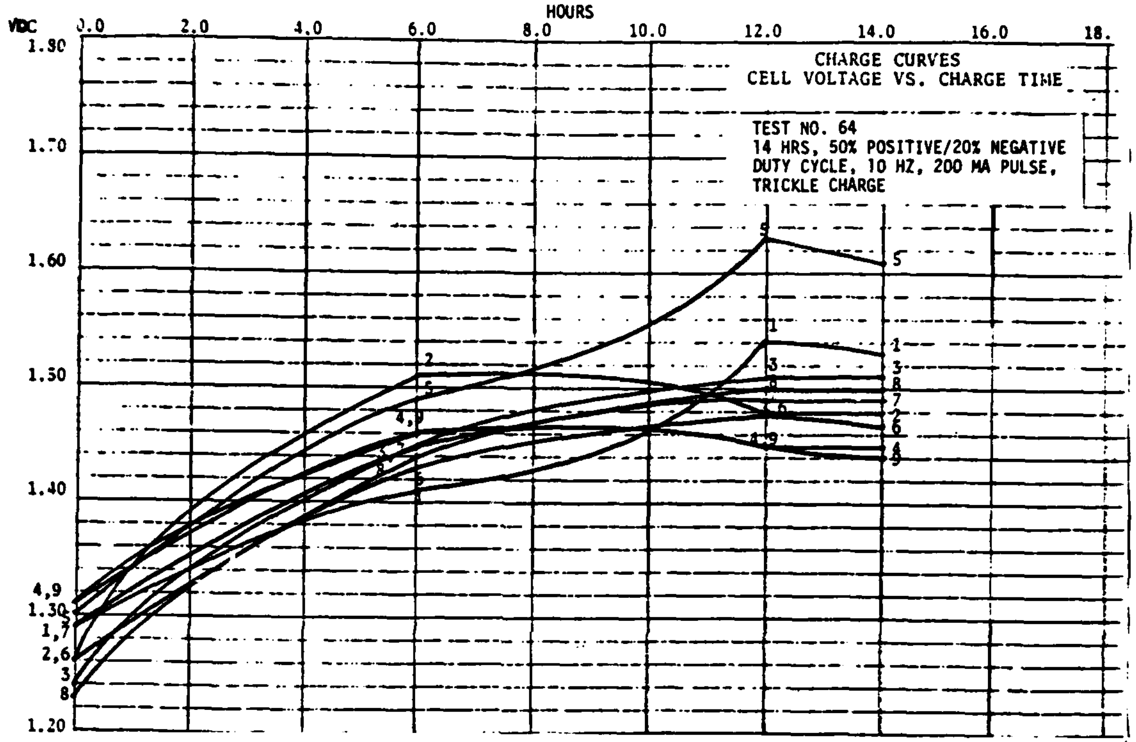


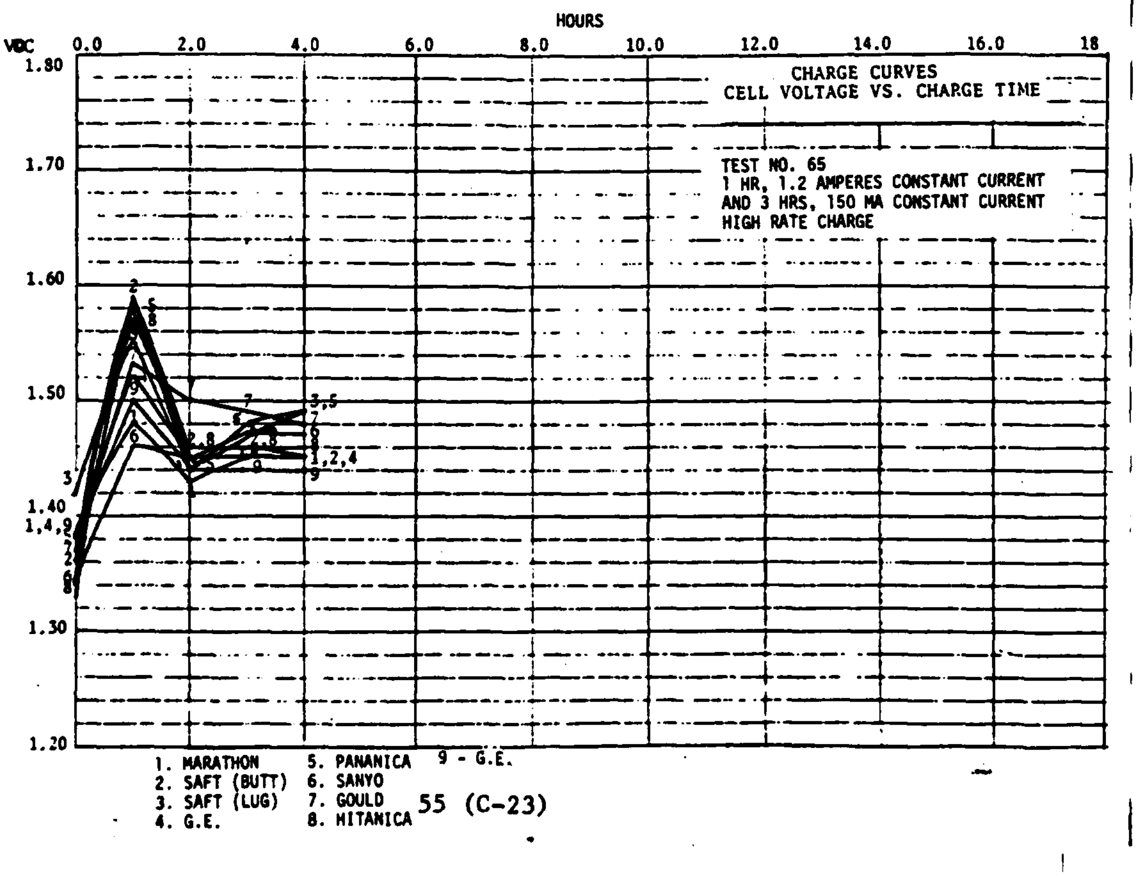
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



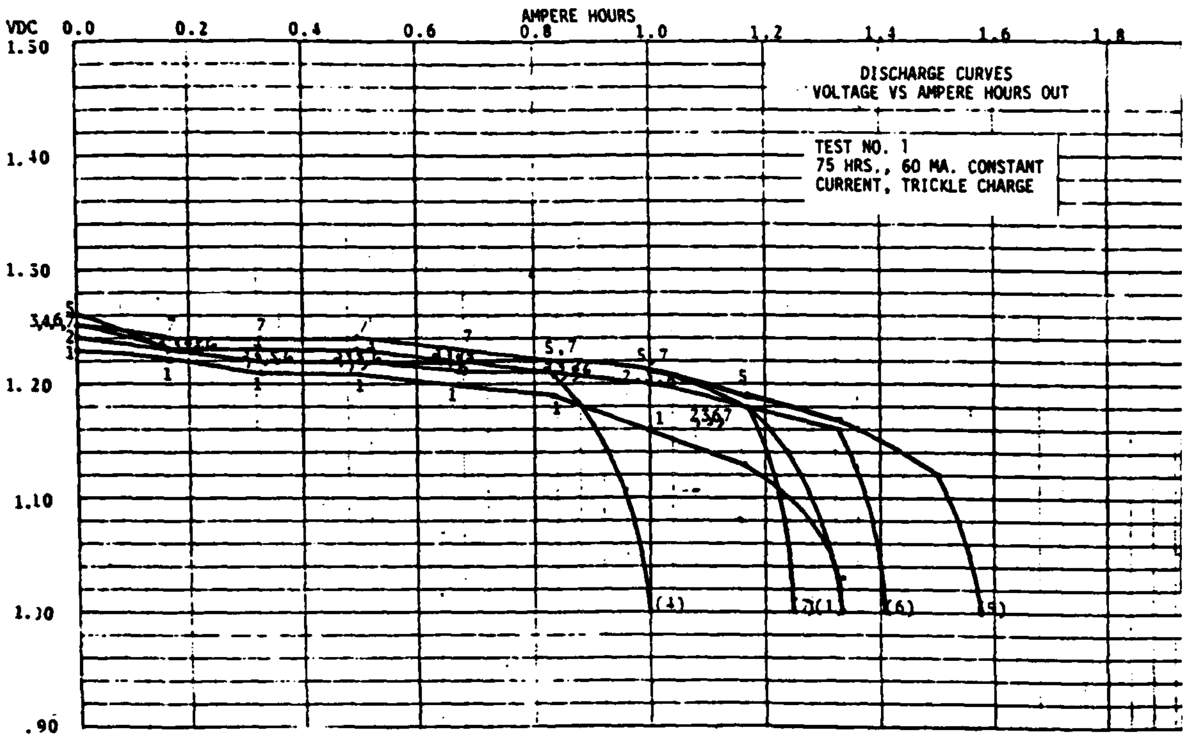


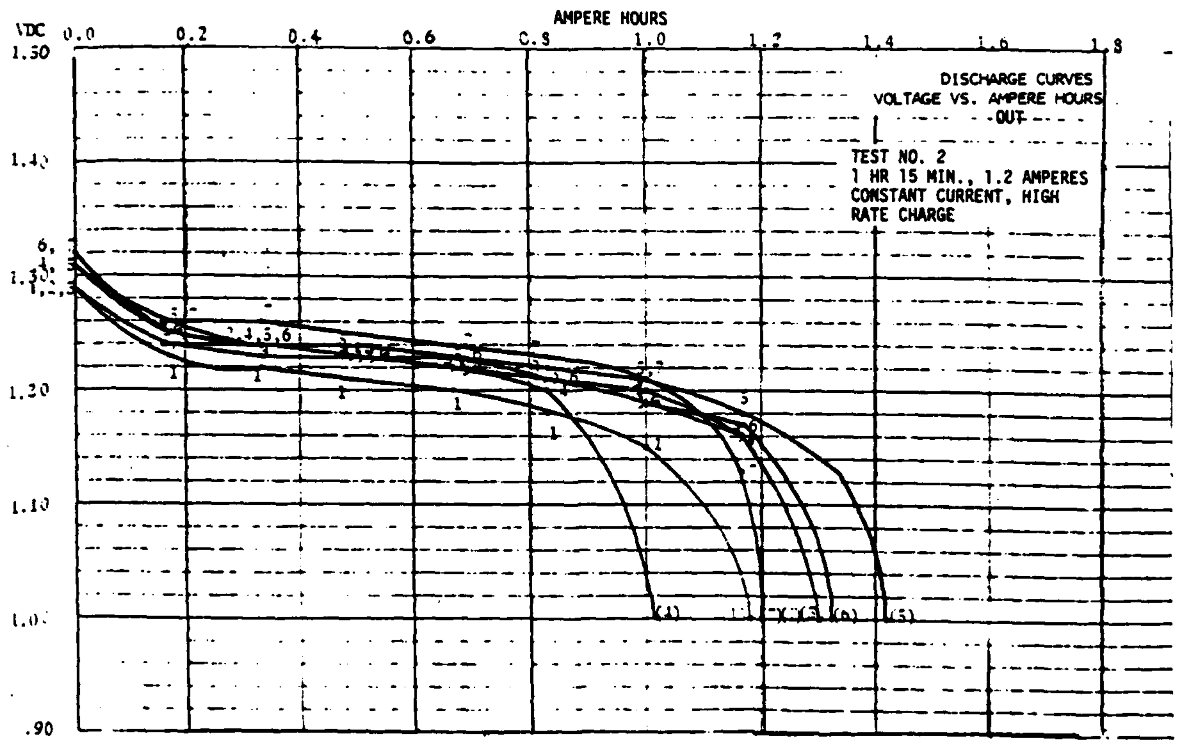
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9 - G.E.


HOURS
VDC
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 64
14 HRS, 50% POSITIVE/20% NEGATIVE
DUTY CYCLE, 10 HZ, 200 MA PULSE,
TRICKLE CHARGE


HOURS
VDC
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 65
1 HR, 1.2 AMPERES CONSTANT CURRENT
AND 3 HRS, 150 MA CONSTANT CURRENT
HIGH RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9 - G.E.

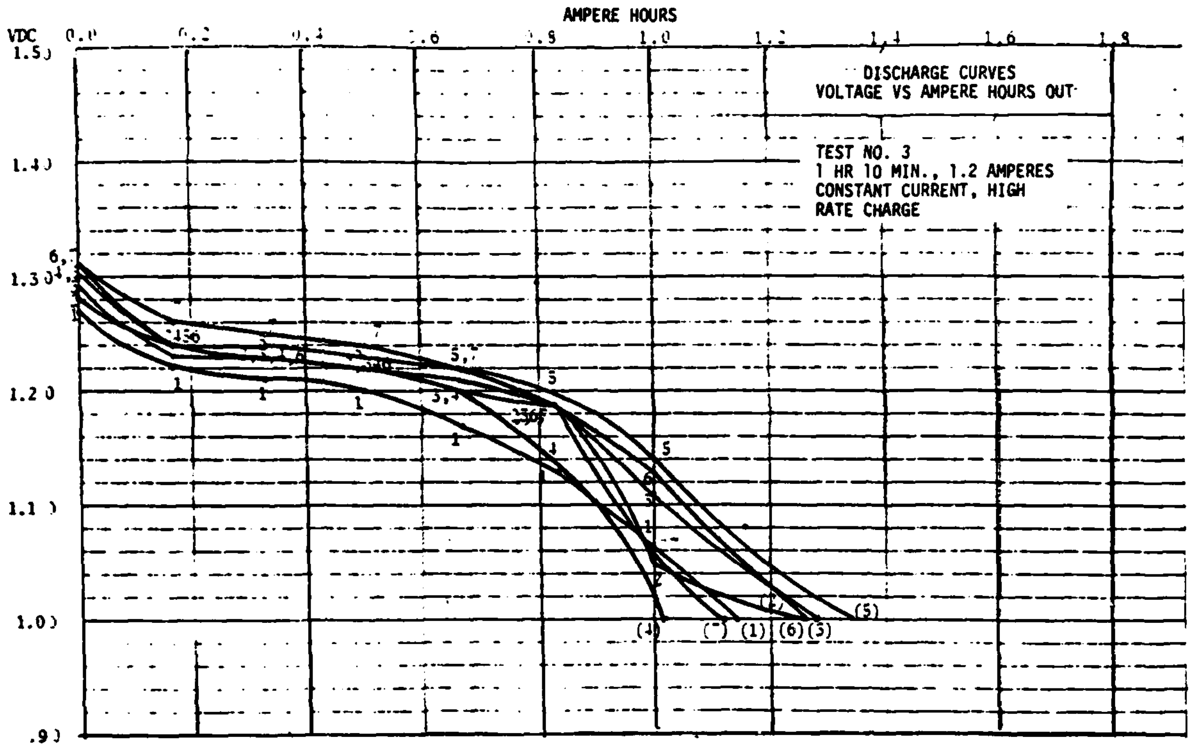
APPENDIX D - CELL DISCHARGE GRAPHS

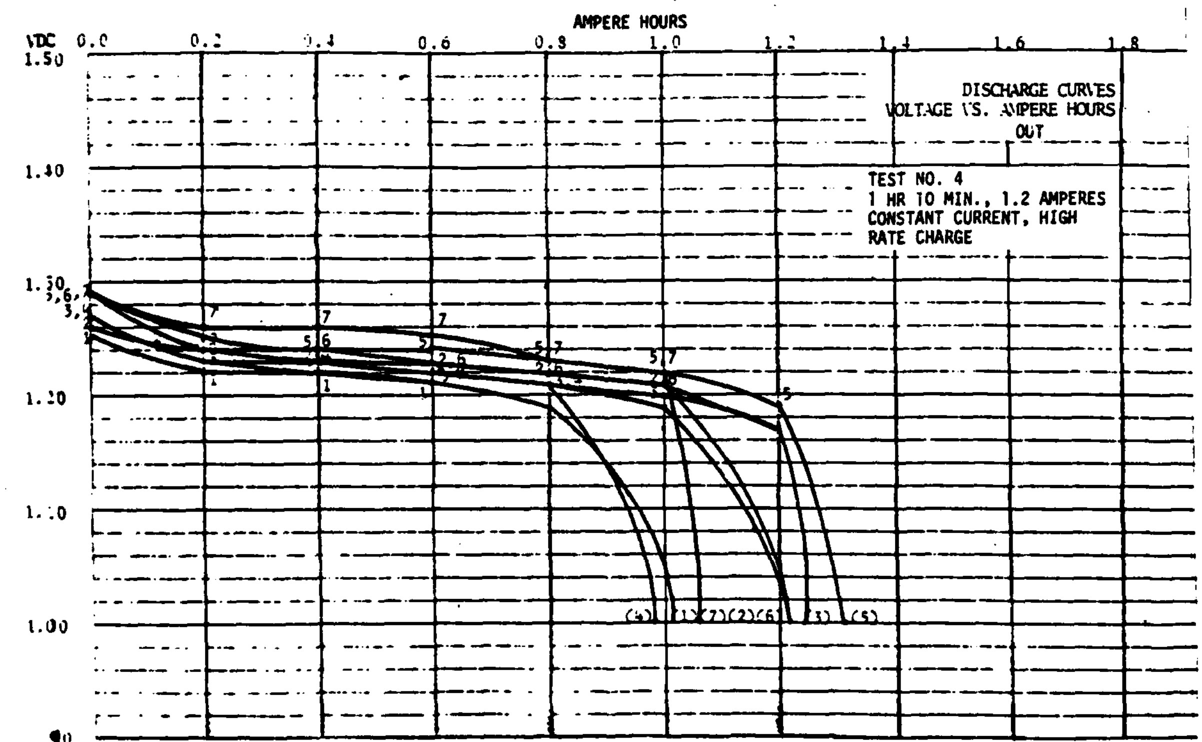




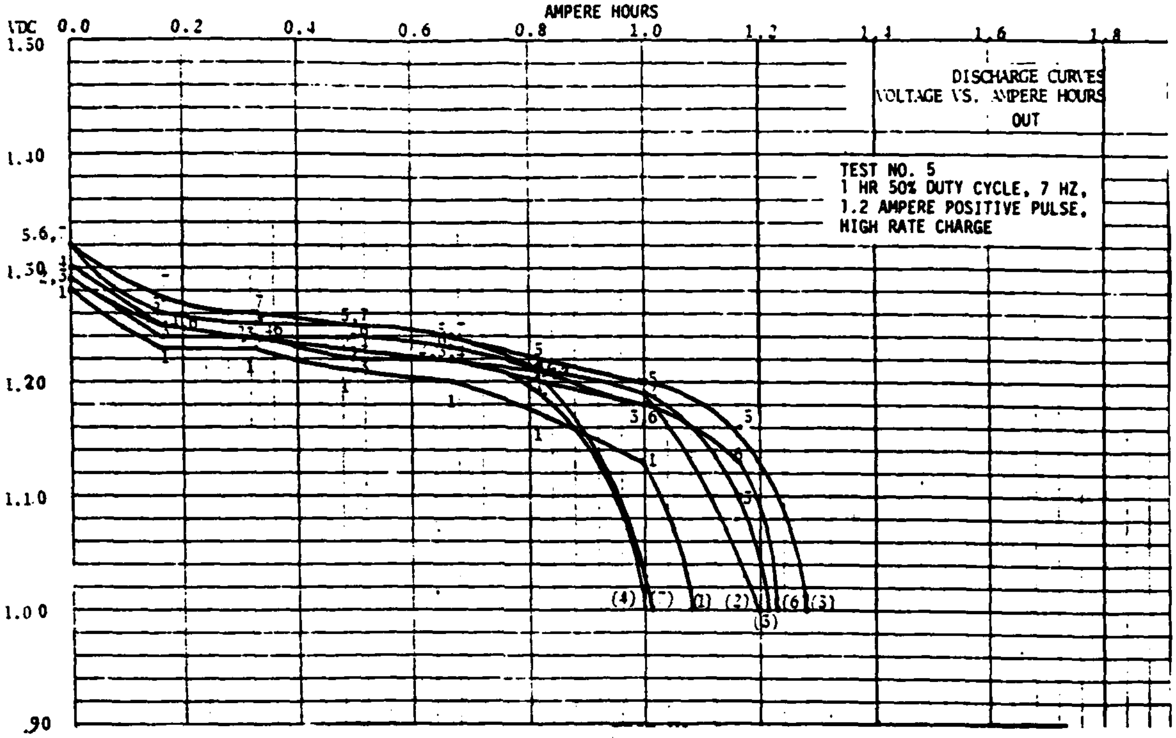
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD

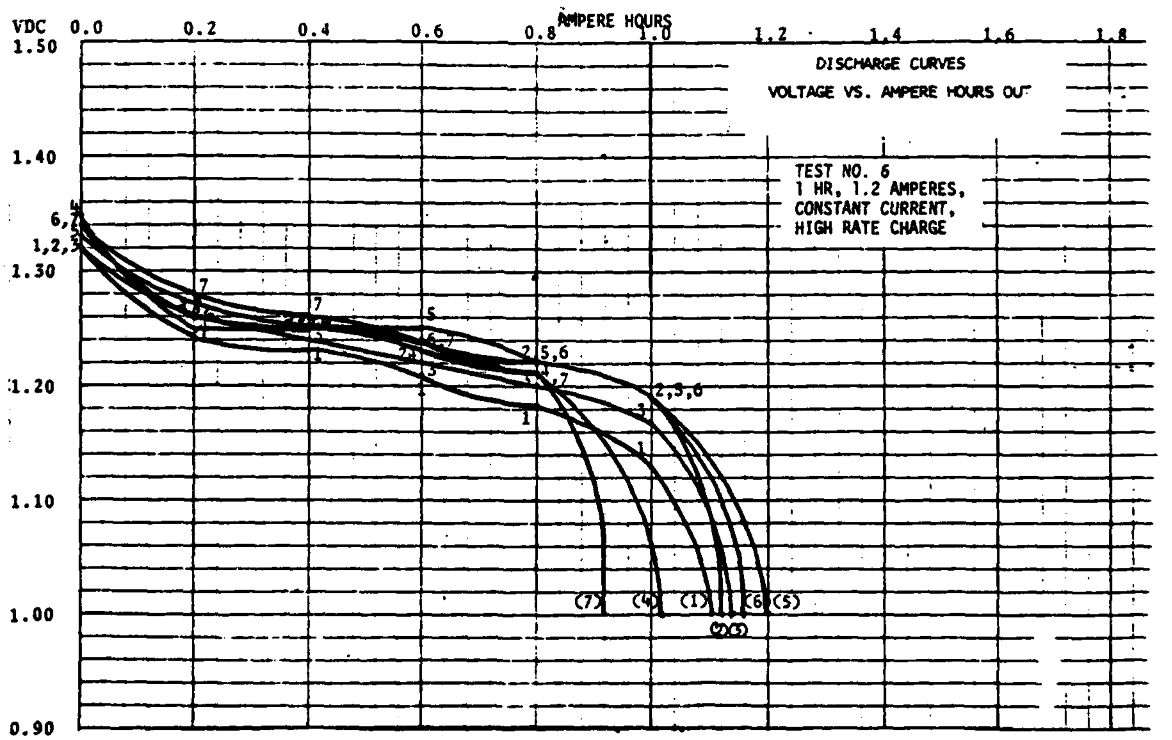
PRECEDING PAGE



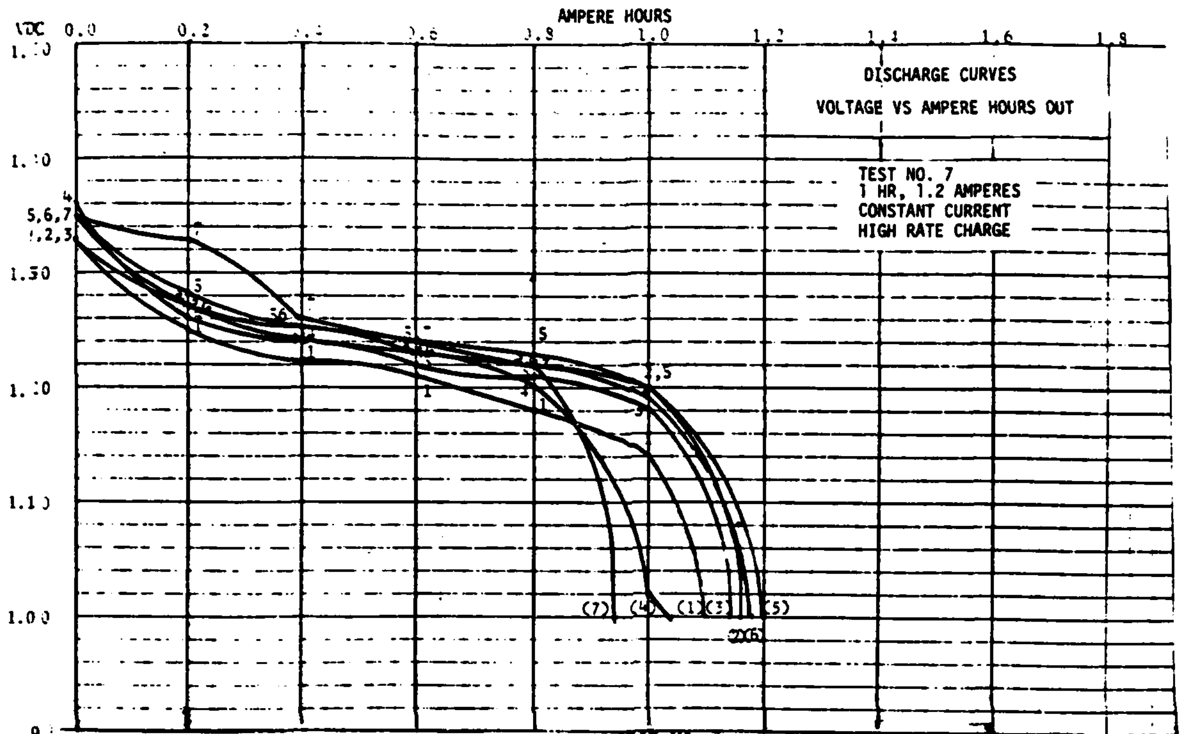


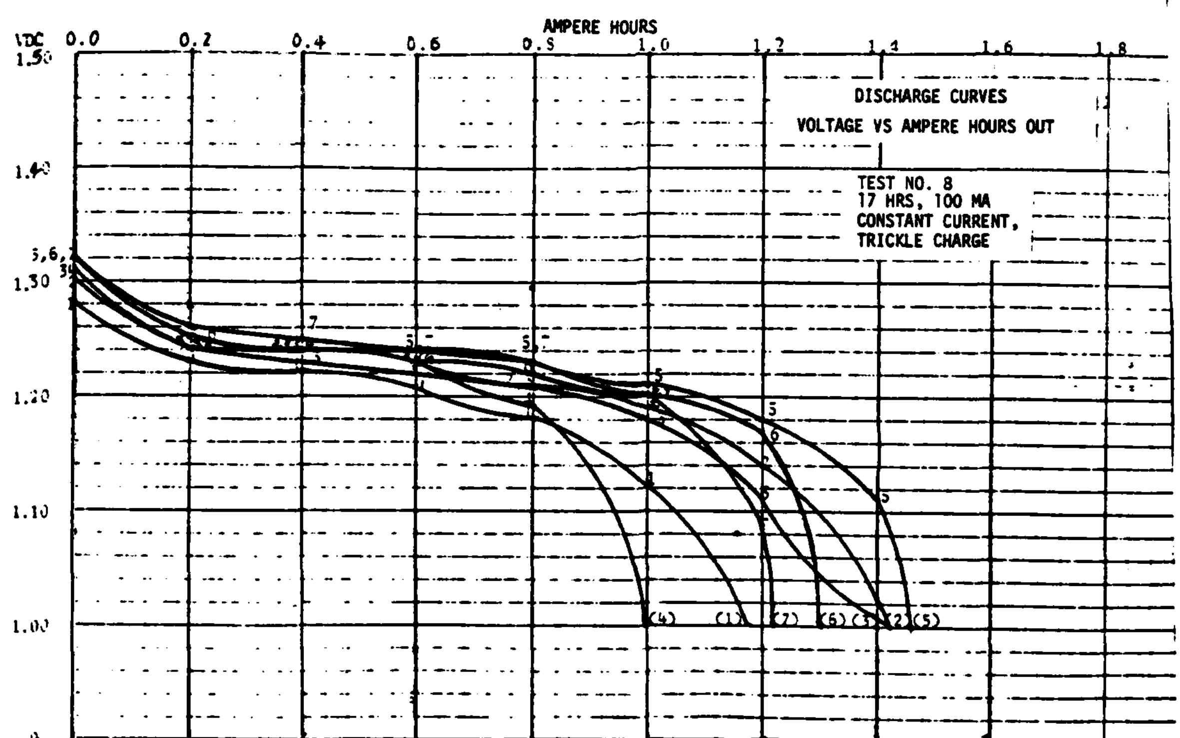
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



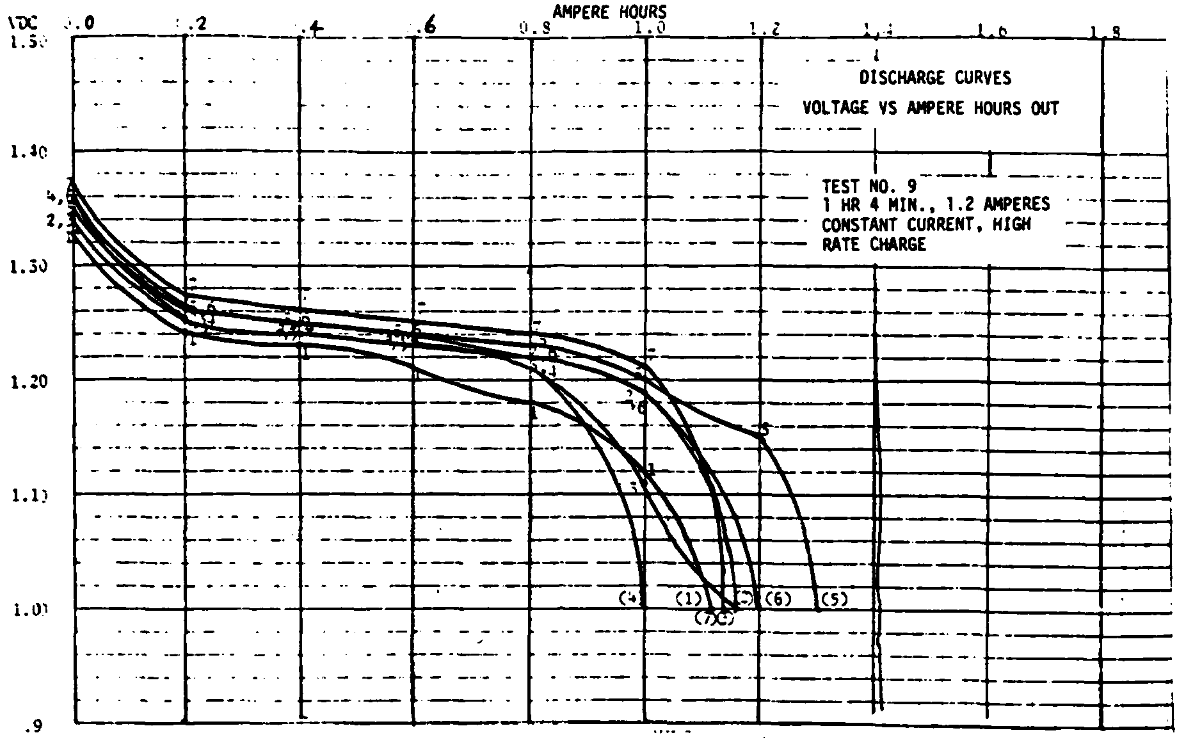


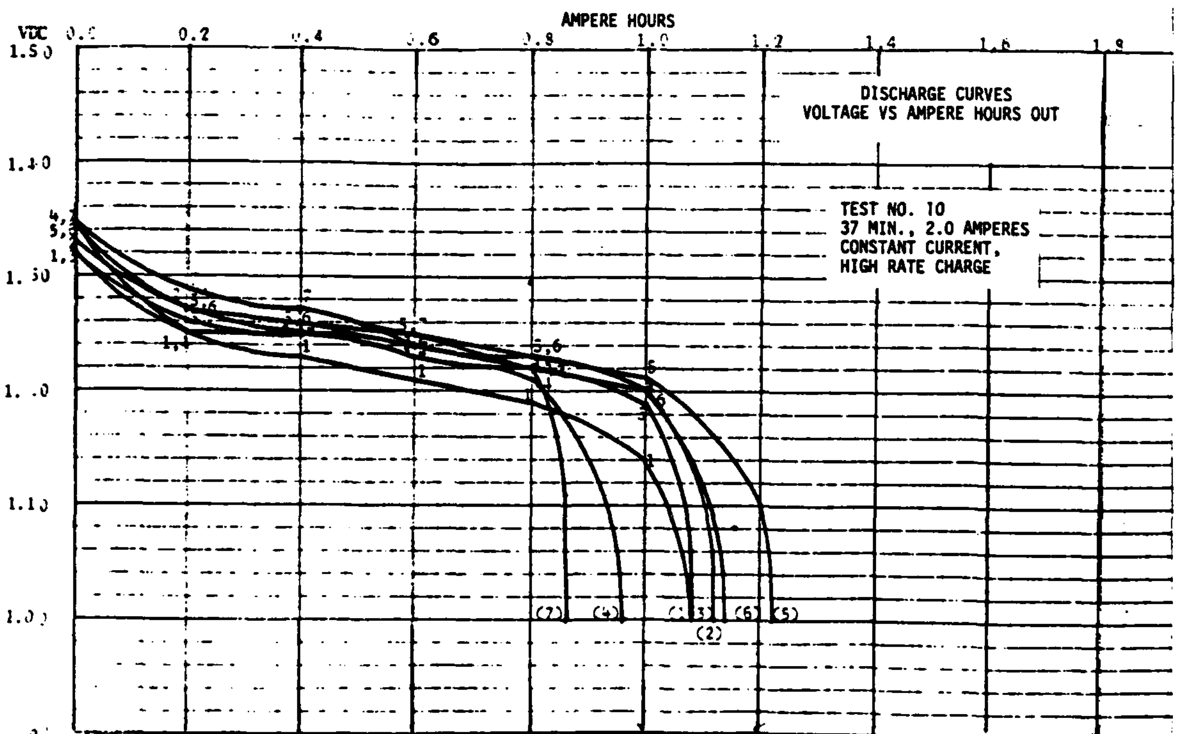
1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E.



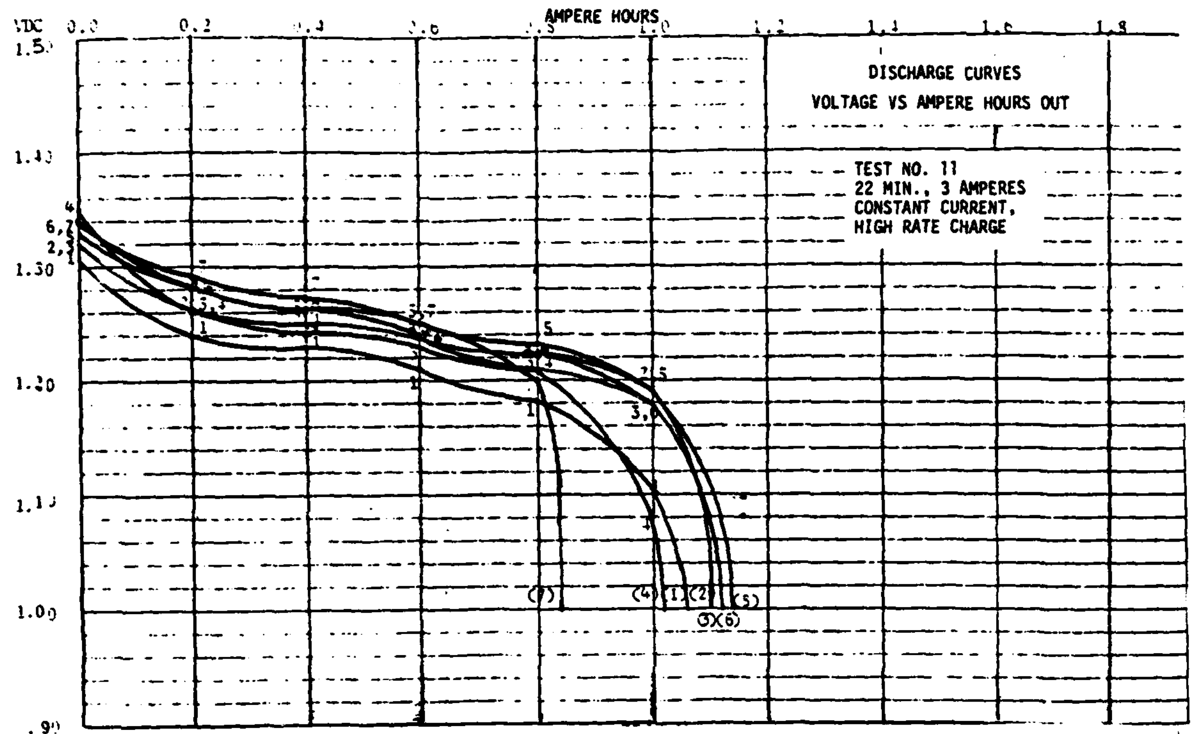


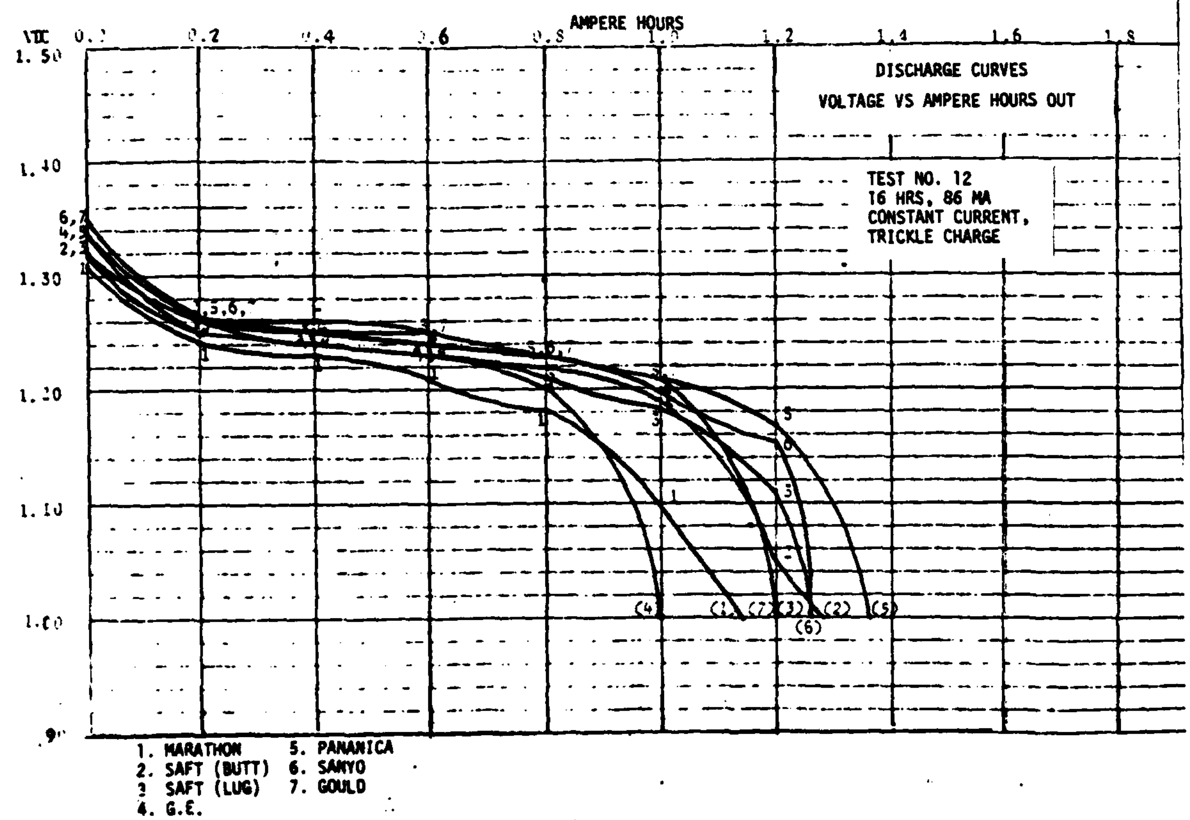
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD

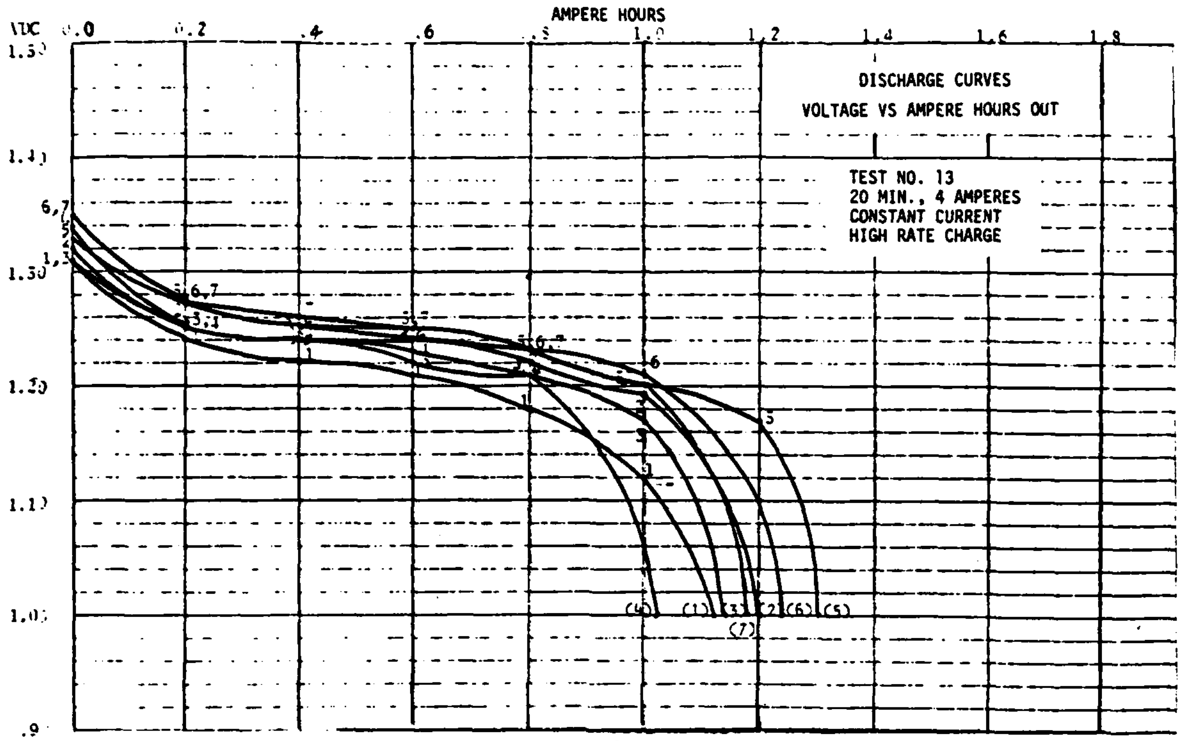


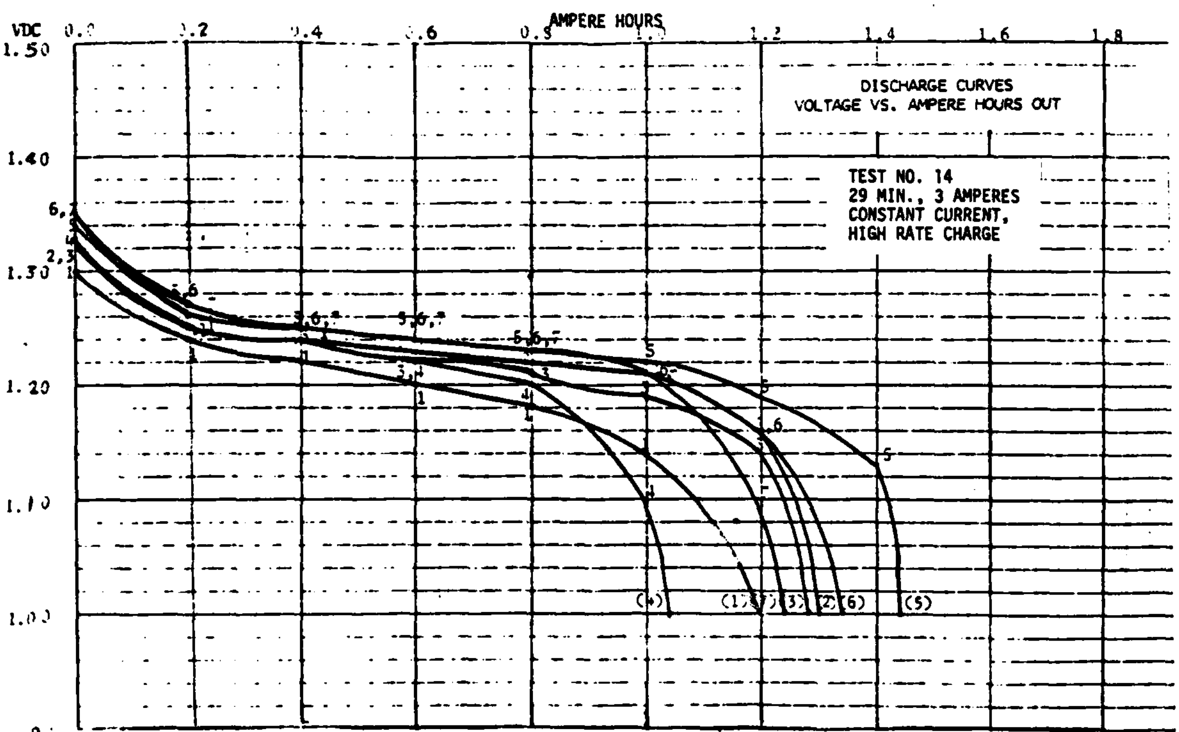


1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD

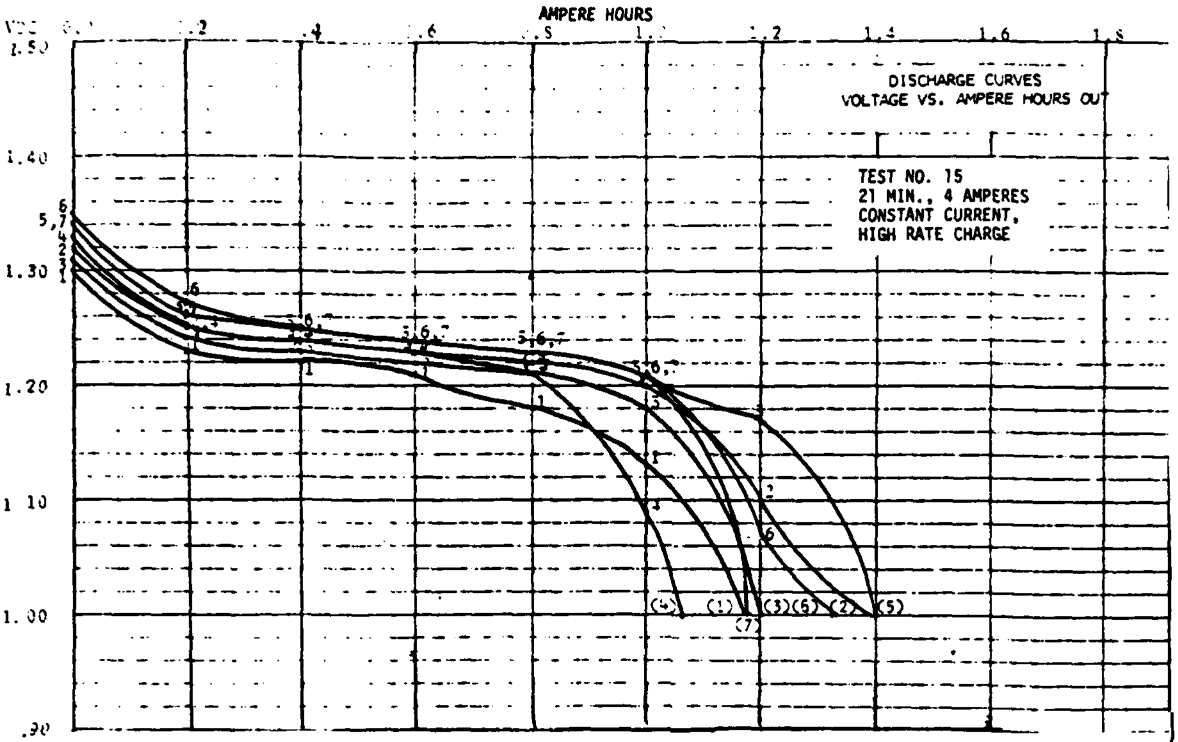

AMPERE HOURS
VDC
DISCHARGE CURVES
VOLTAGE VS AMPERE HOURS OUT
TEST NO. 11
22 MIN., 3 AMPERES
CONSTANT CURRENT,
HIGH RATE CHARGE

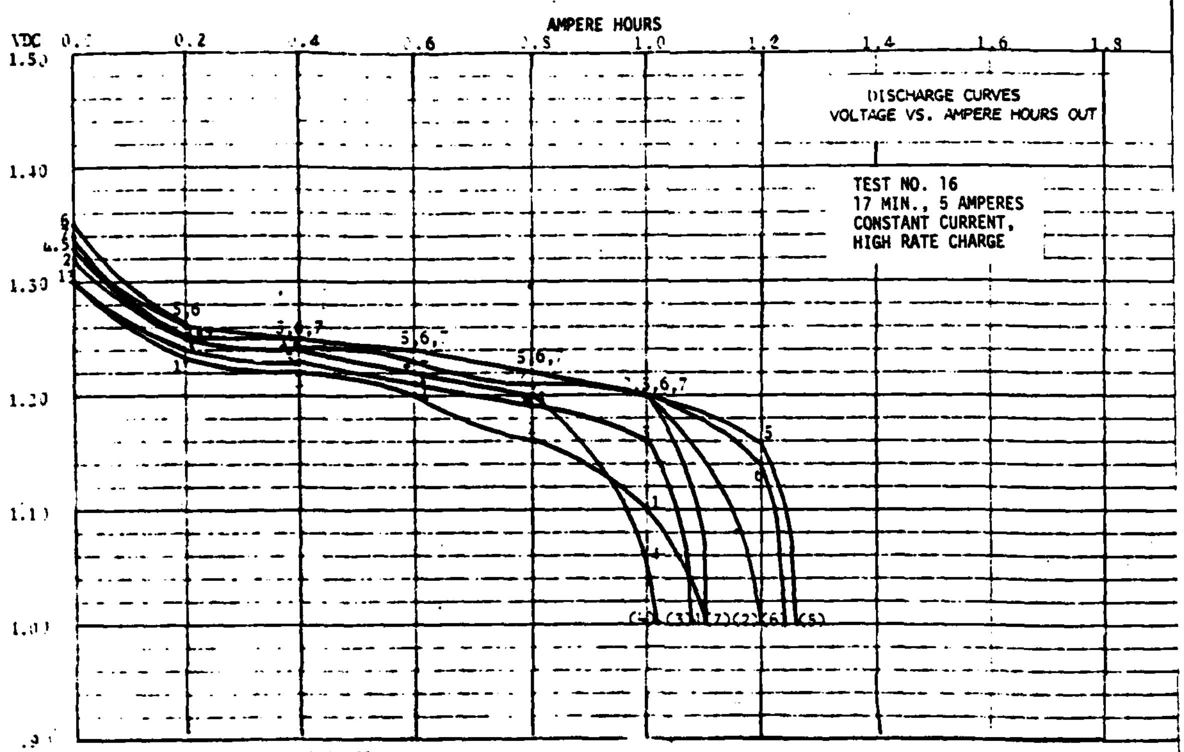

AMPERE HOURS
VDC
DISCHARGE CURVES
VOLTAGE VS AMPERE HOURS OUT
TEST NO. 12
16 HRS, 86 MA
CONSTANT CURRENT,
TRICKLE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



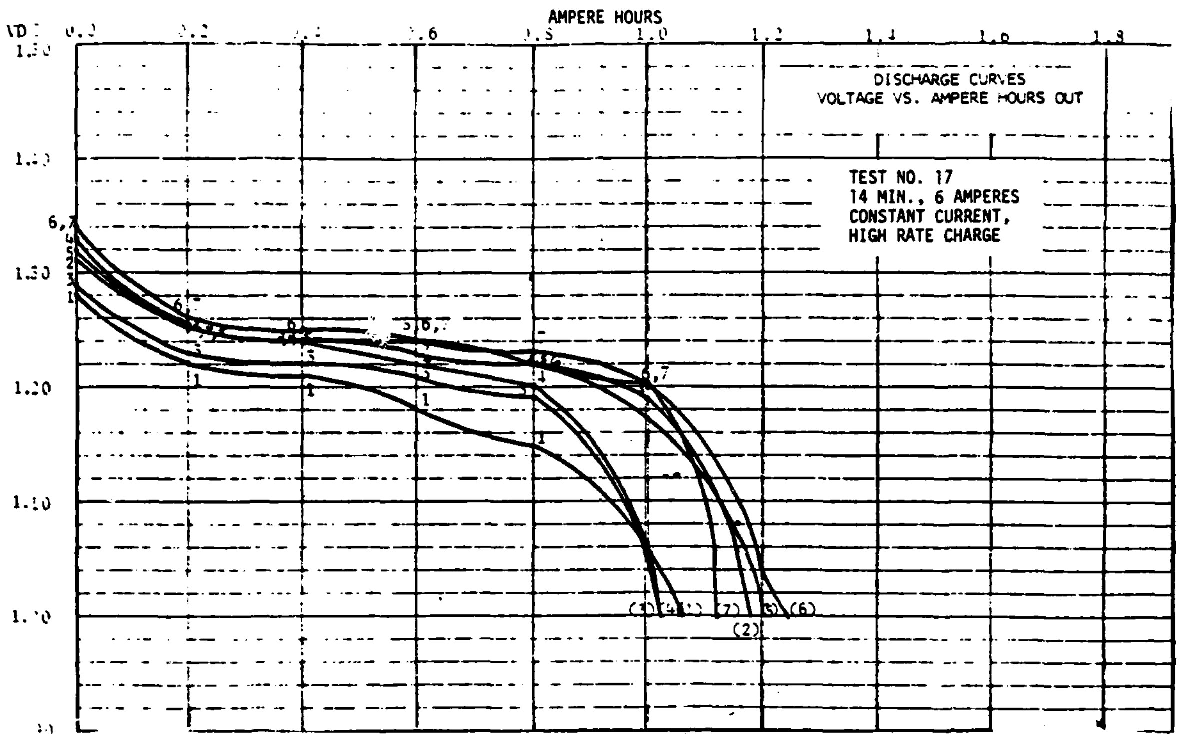


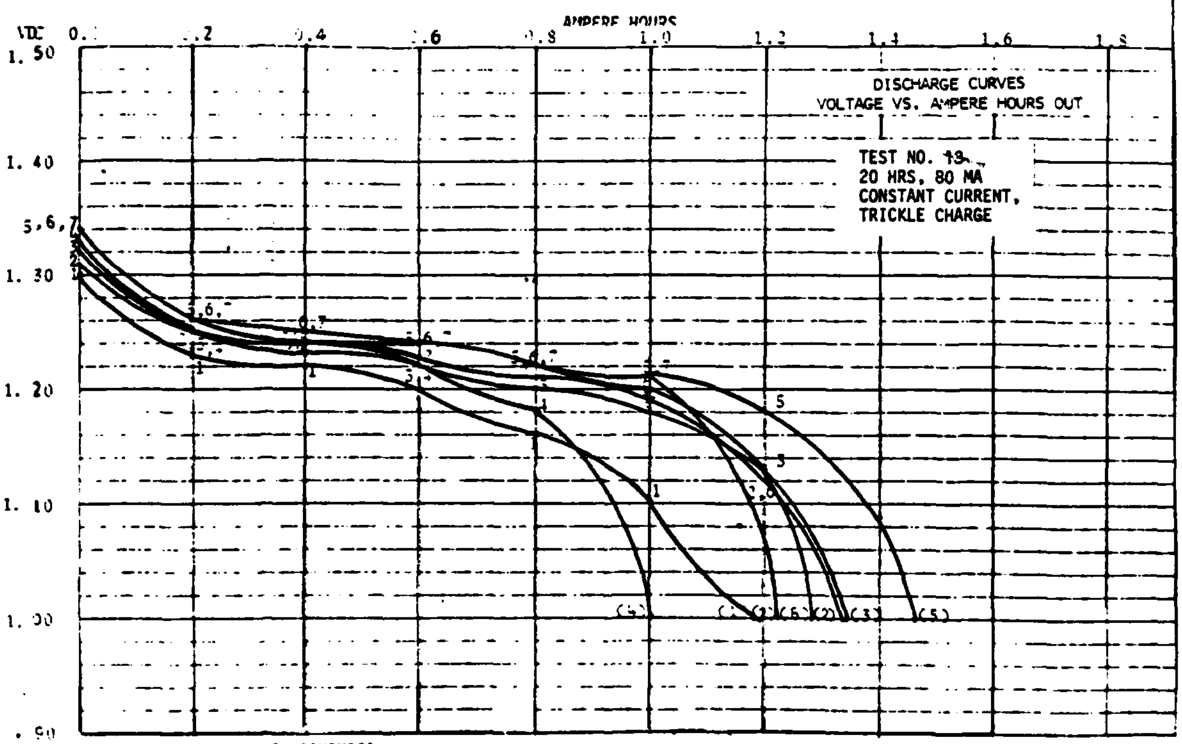
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



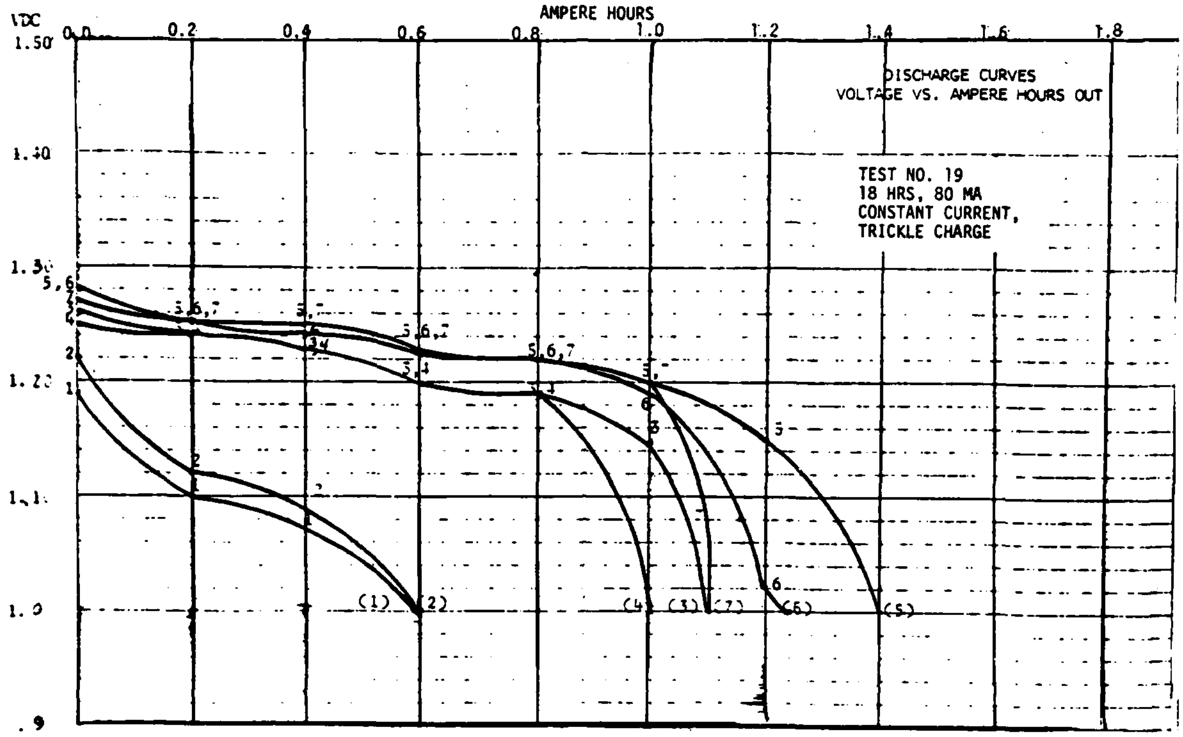


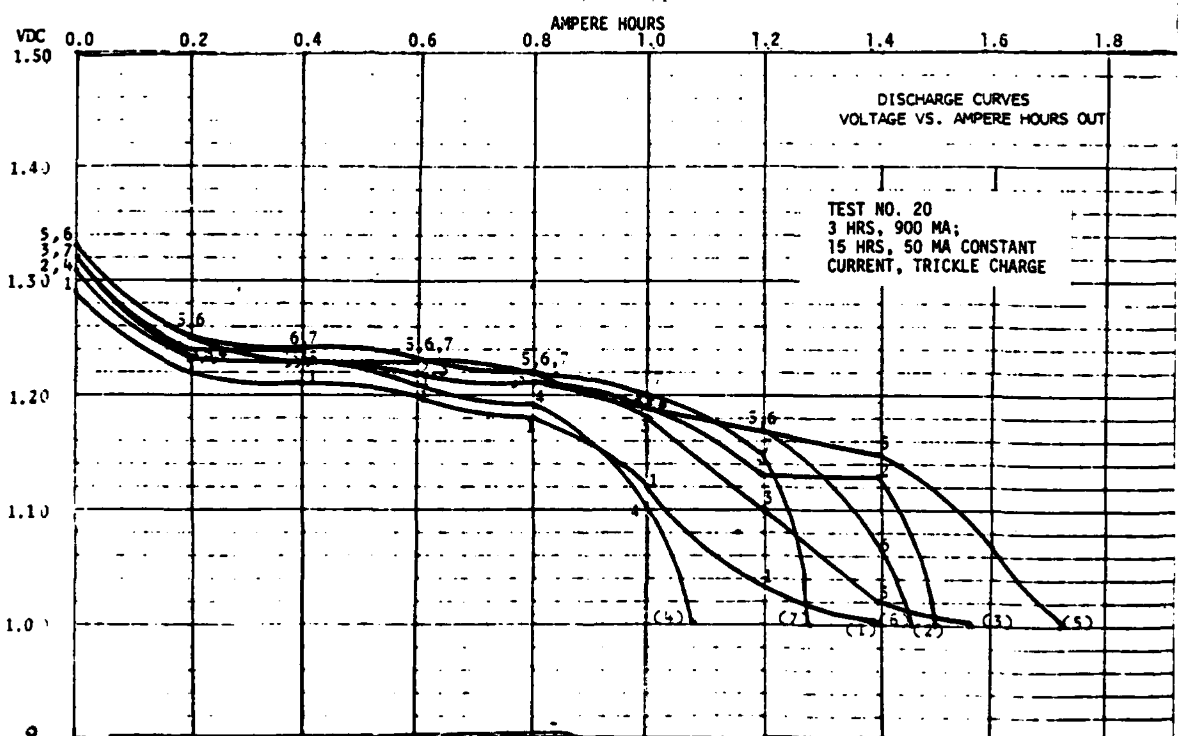
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



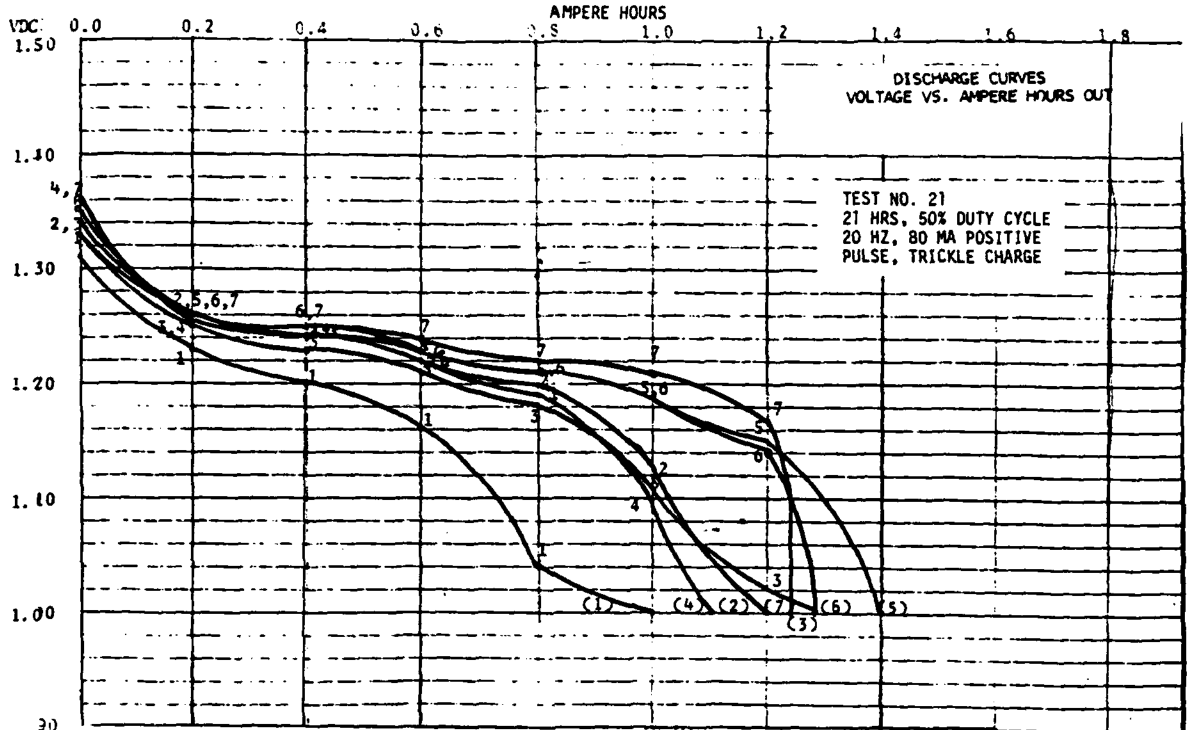


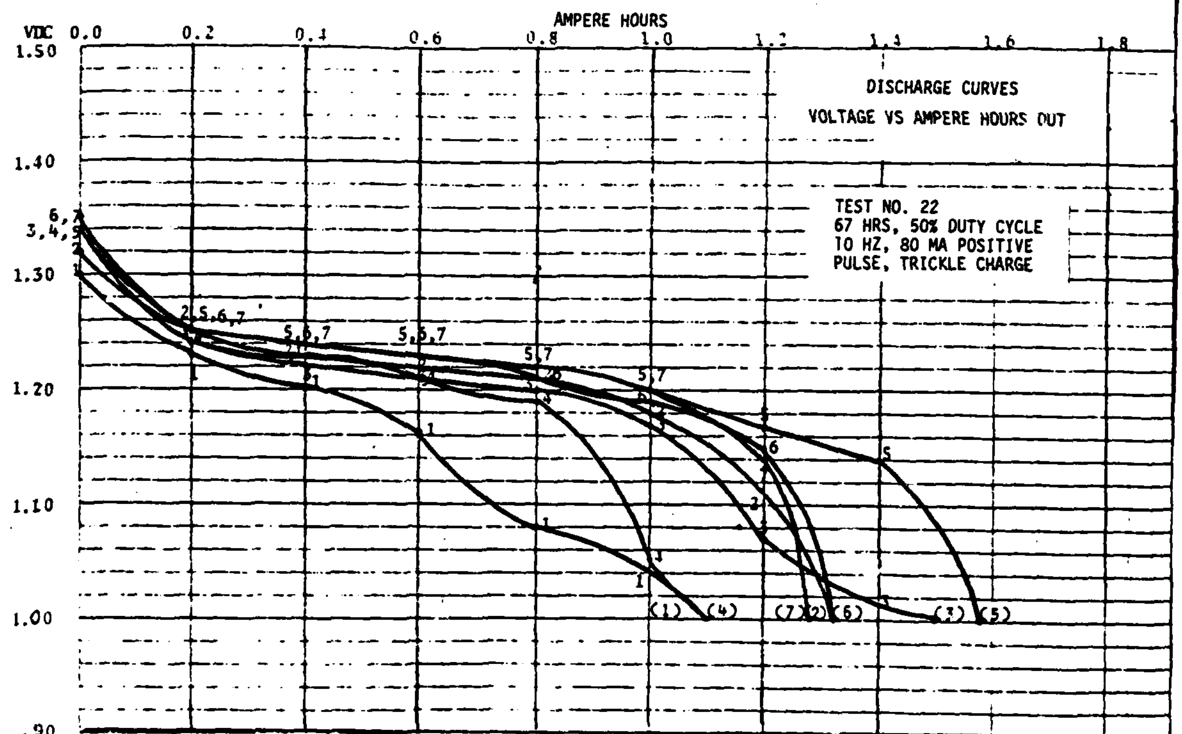
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



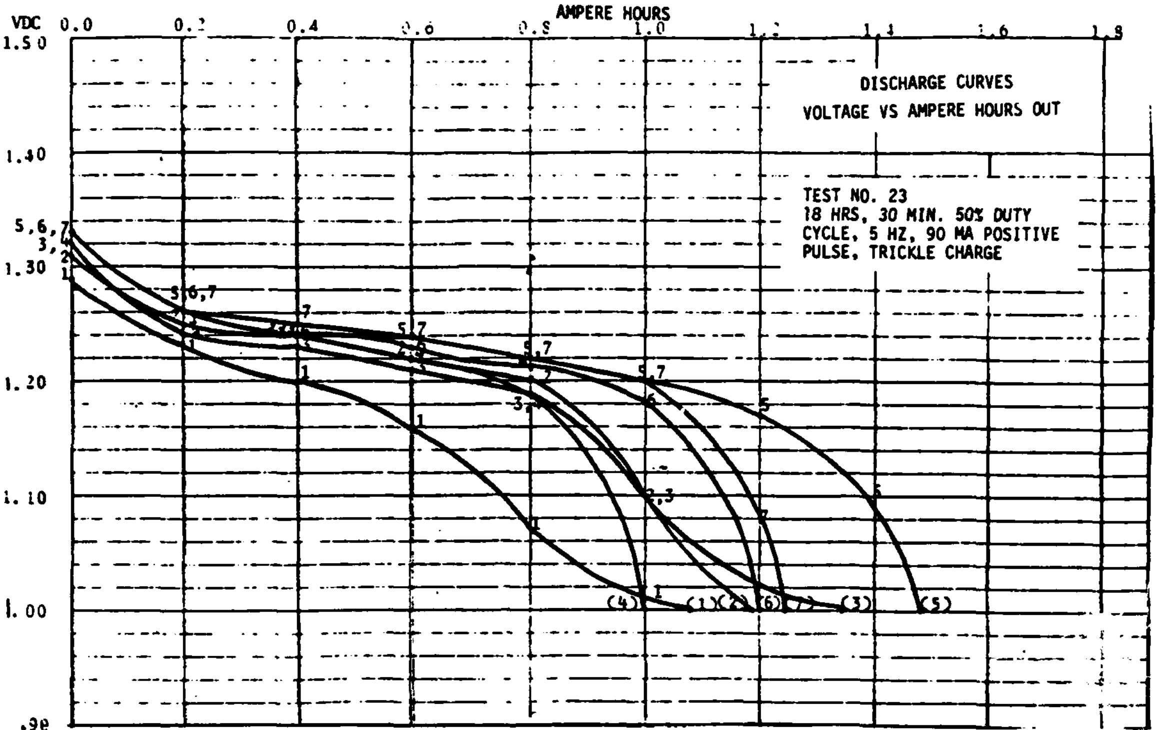


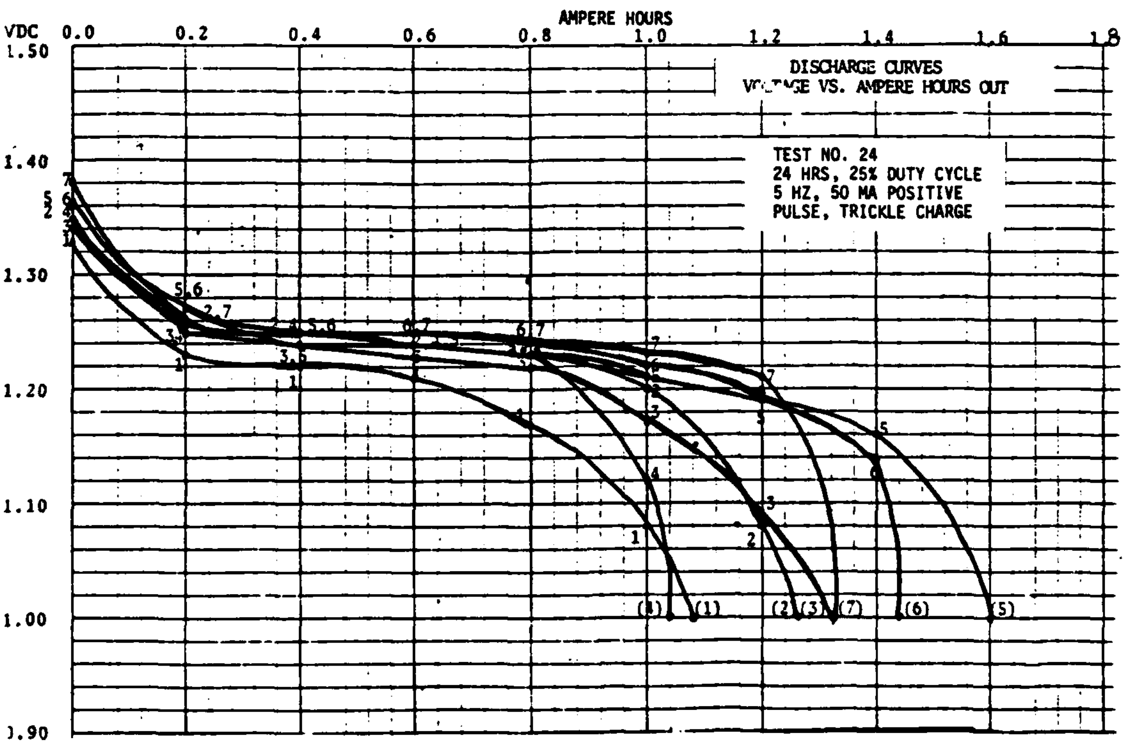
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



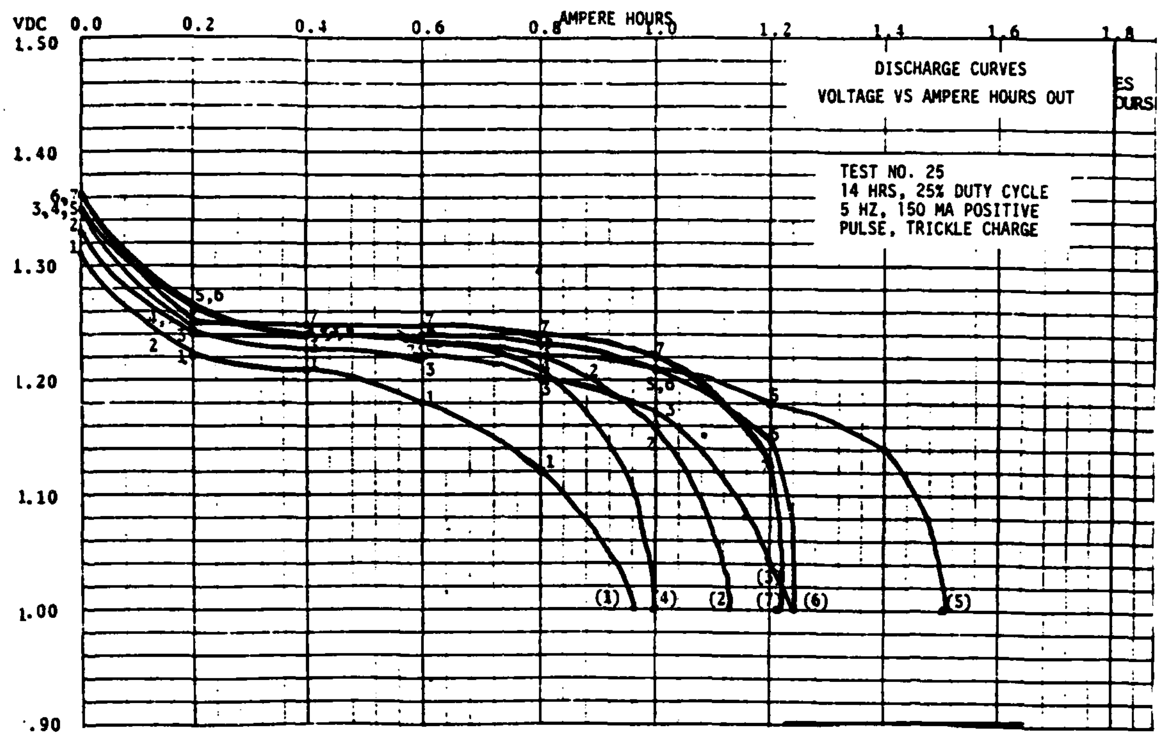


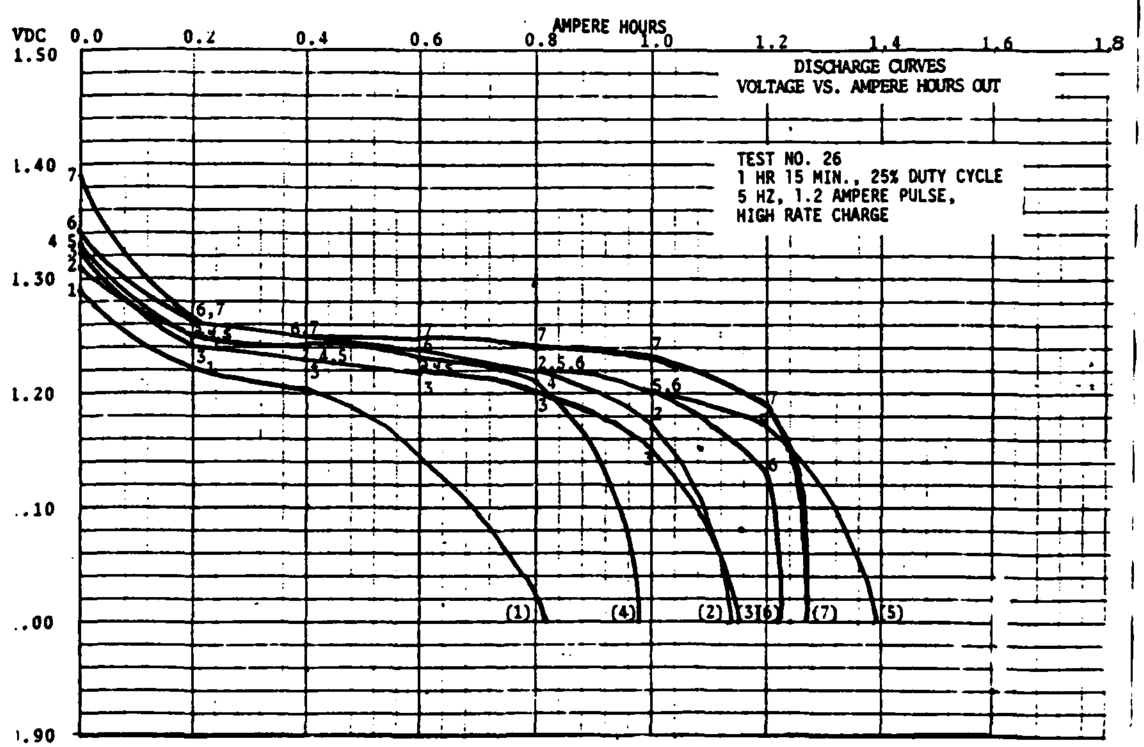
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



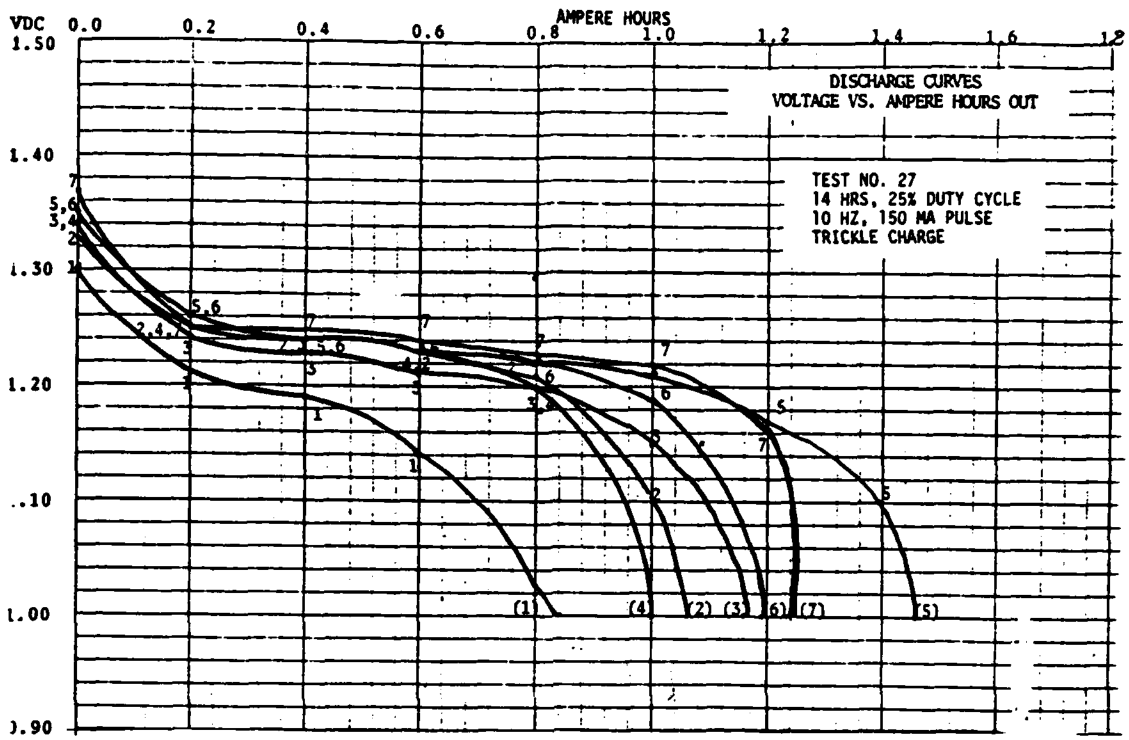


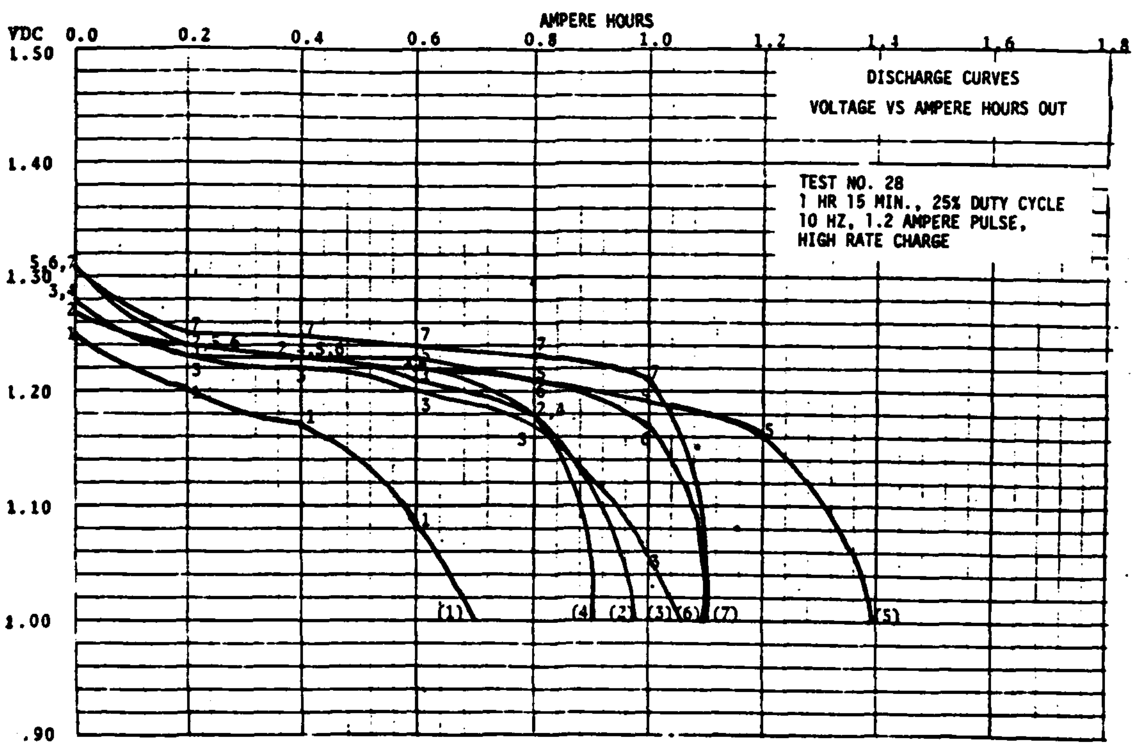
1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E.



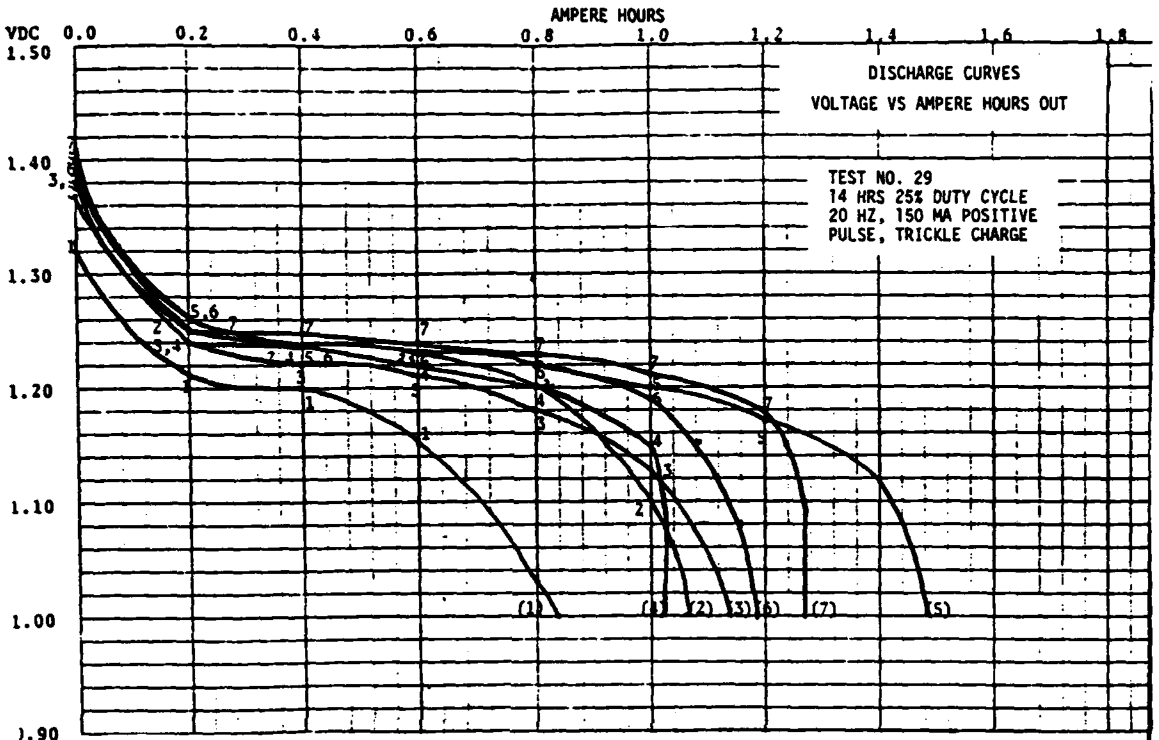


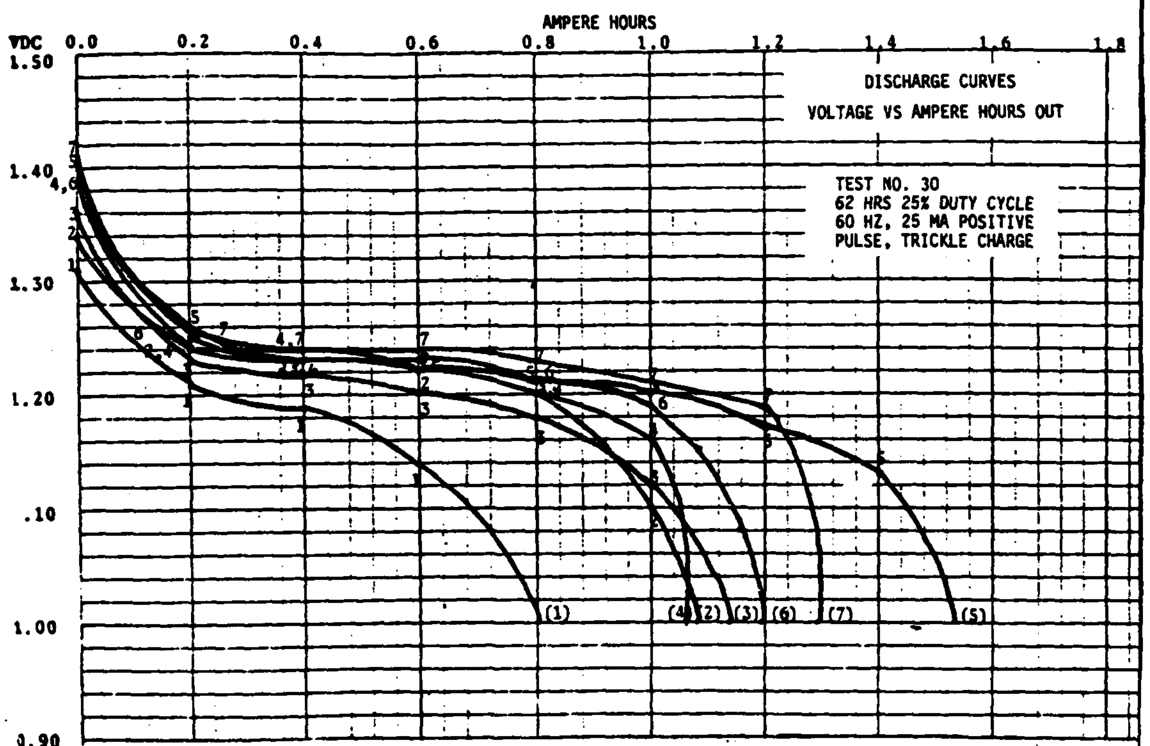
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



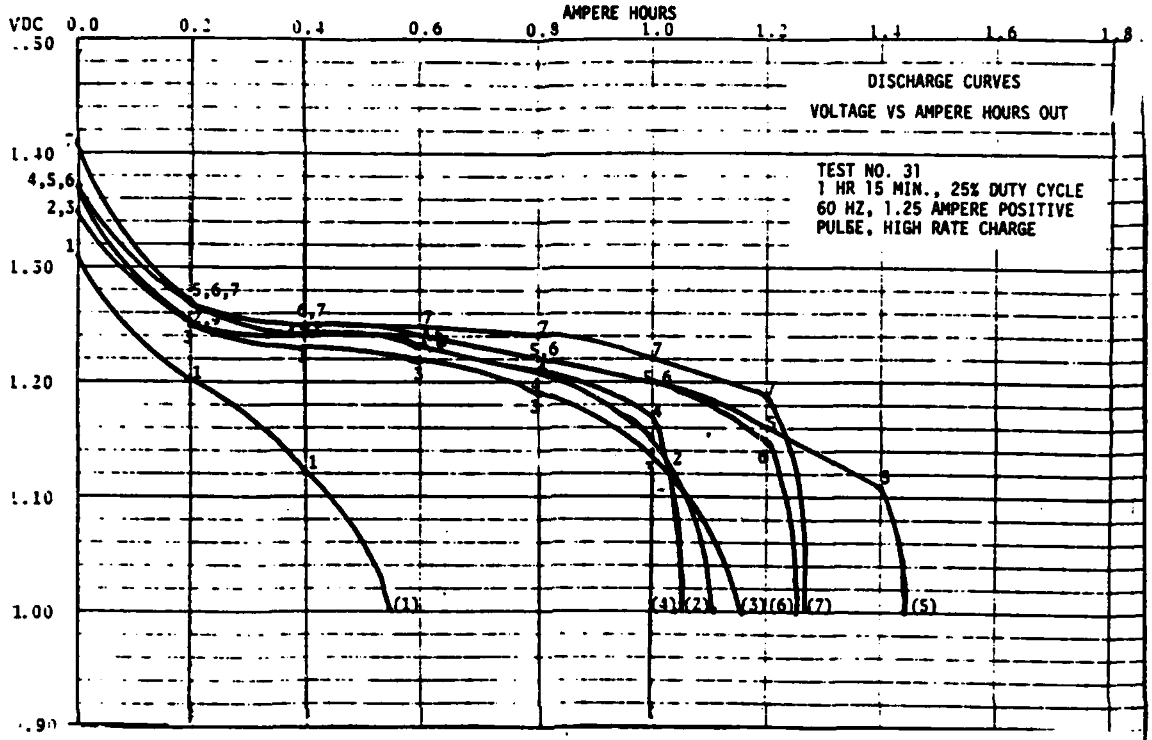


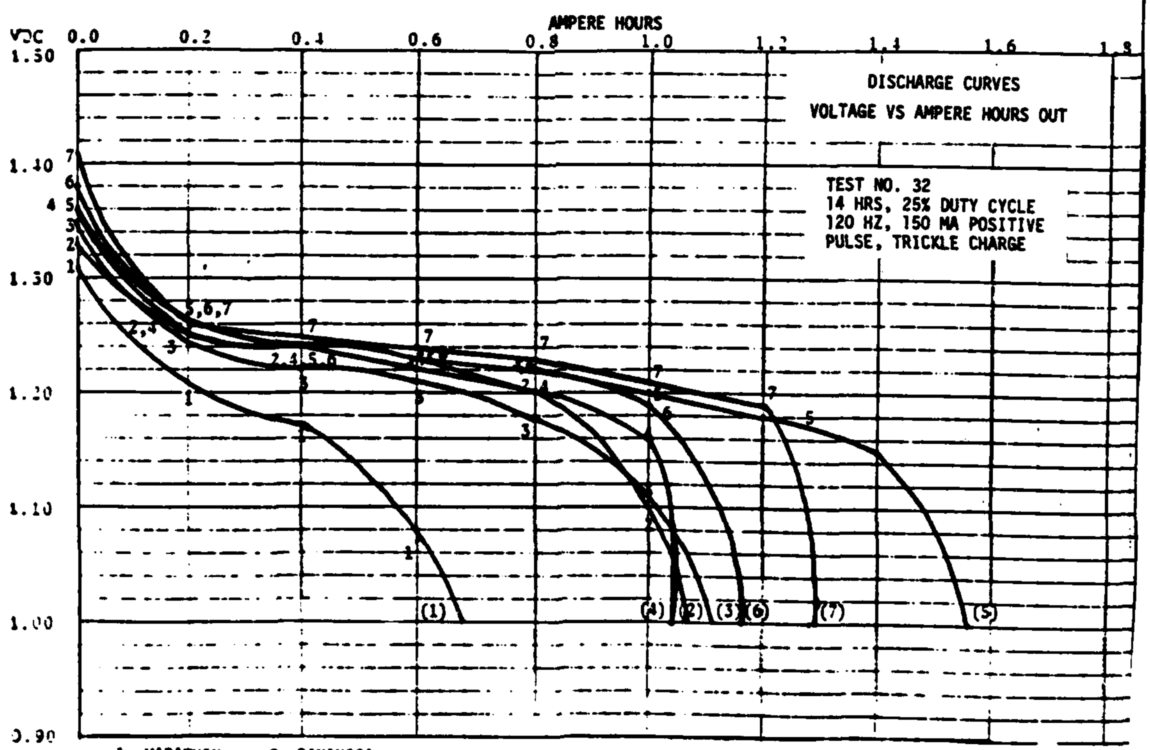
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



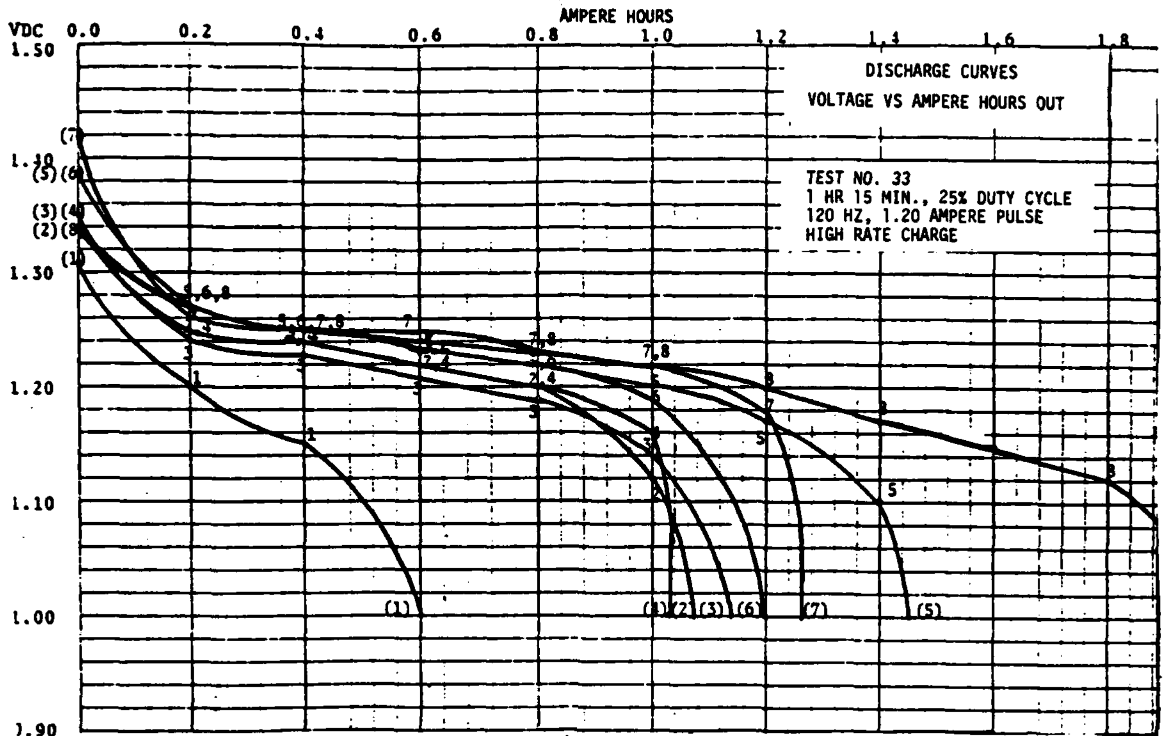


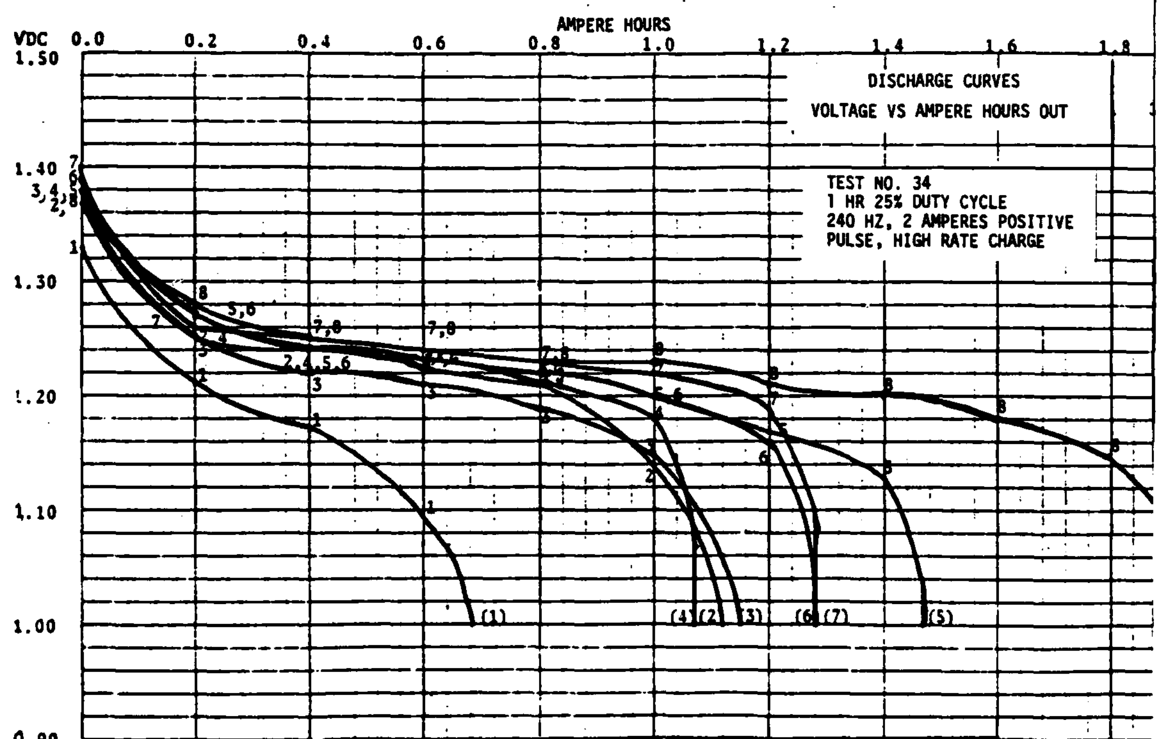
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD



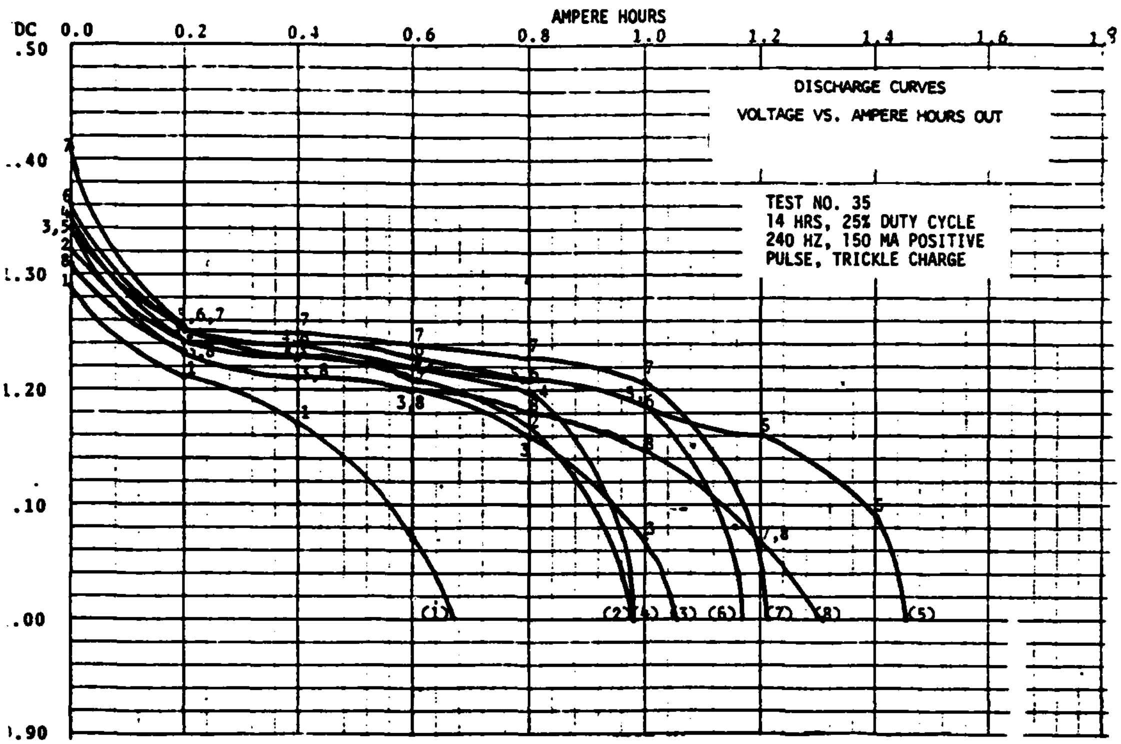


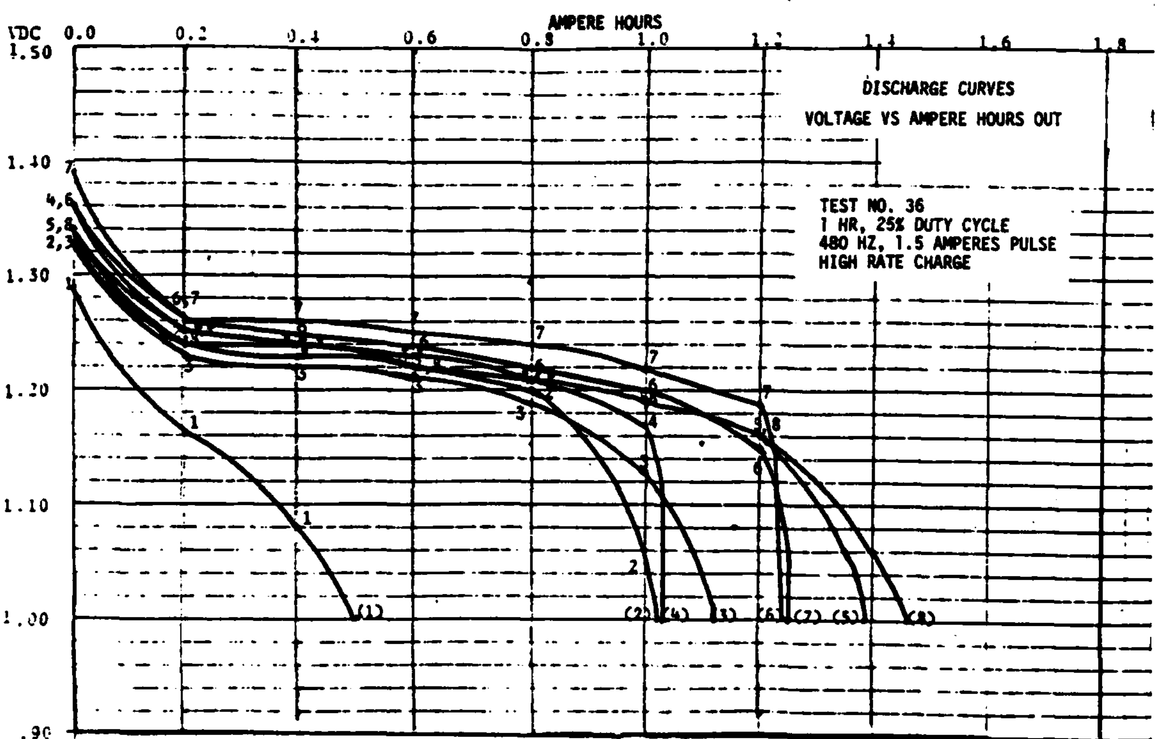
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD



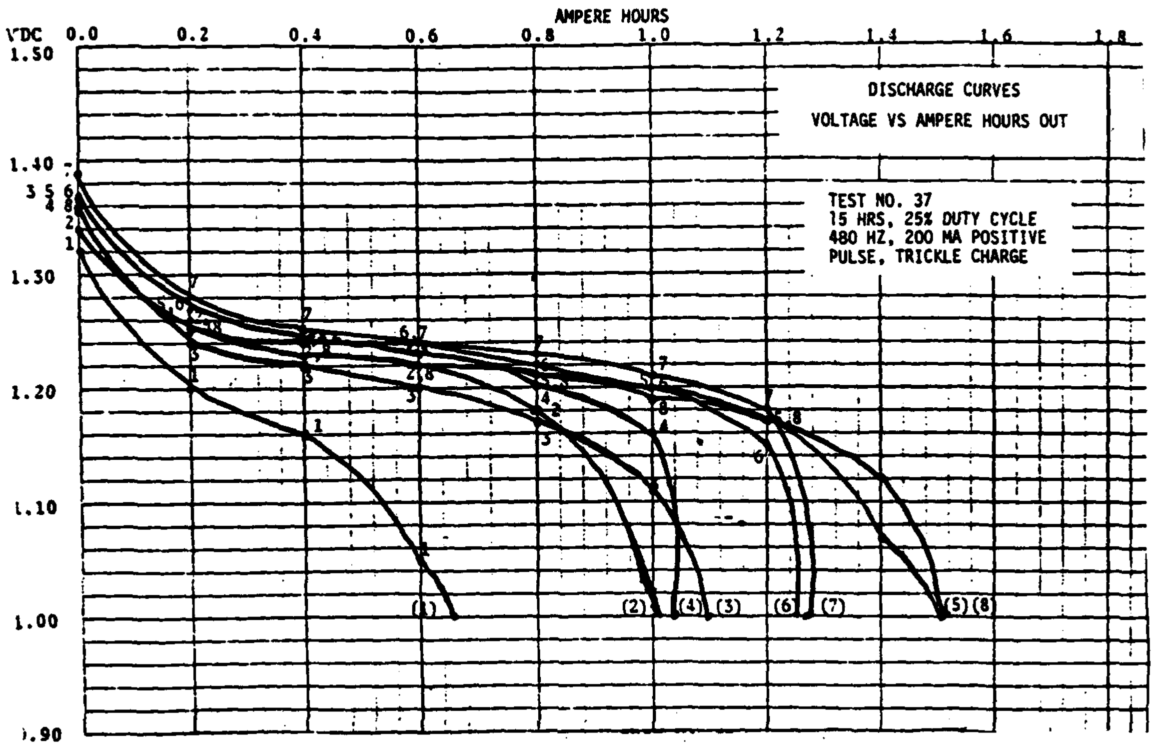


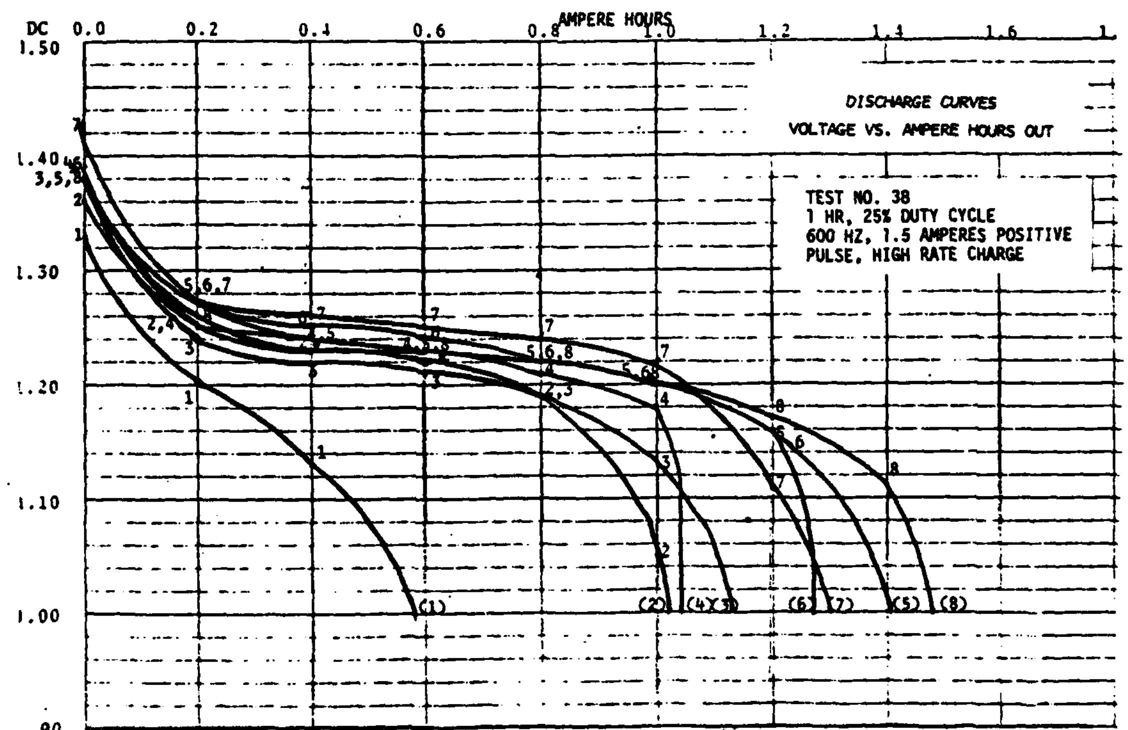
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



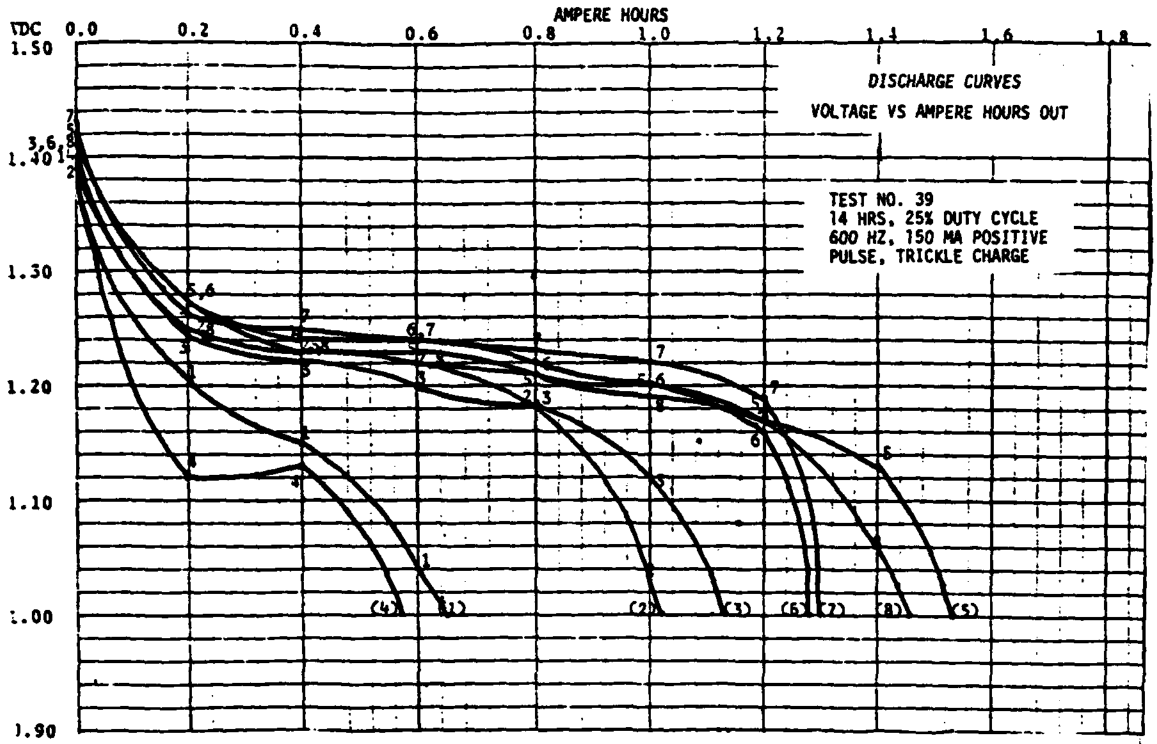


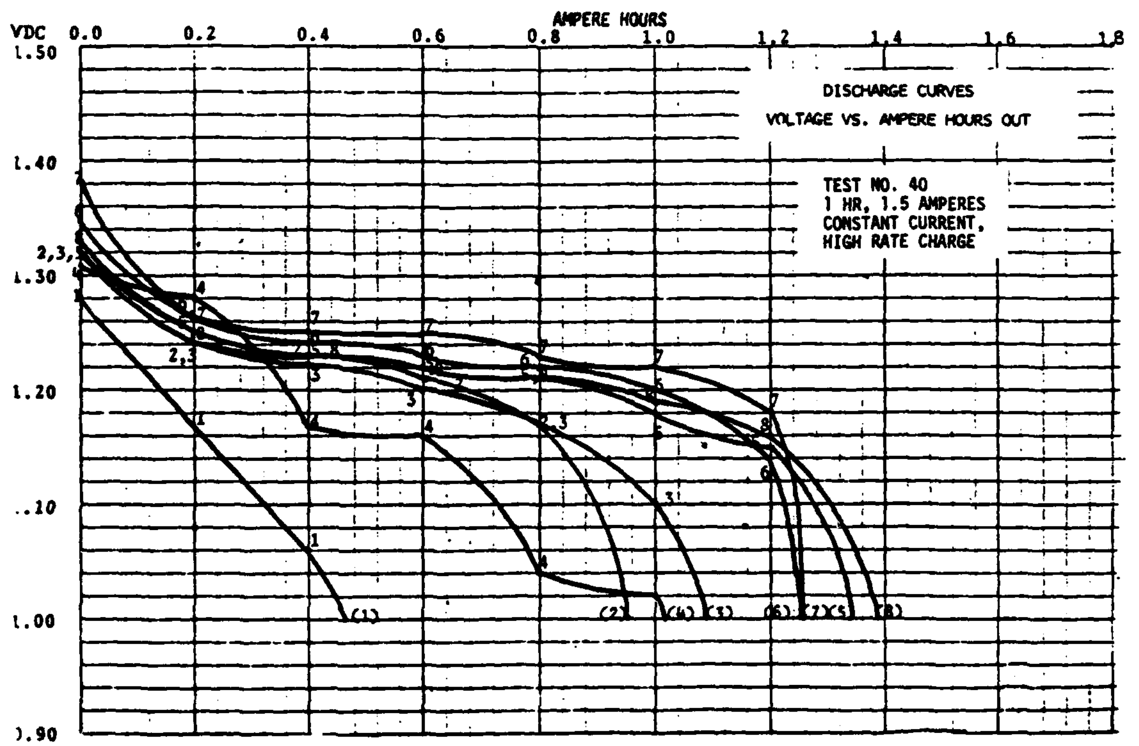
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



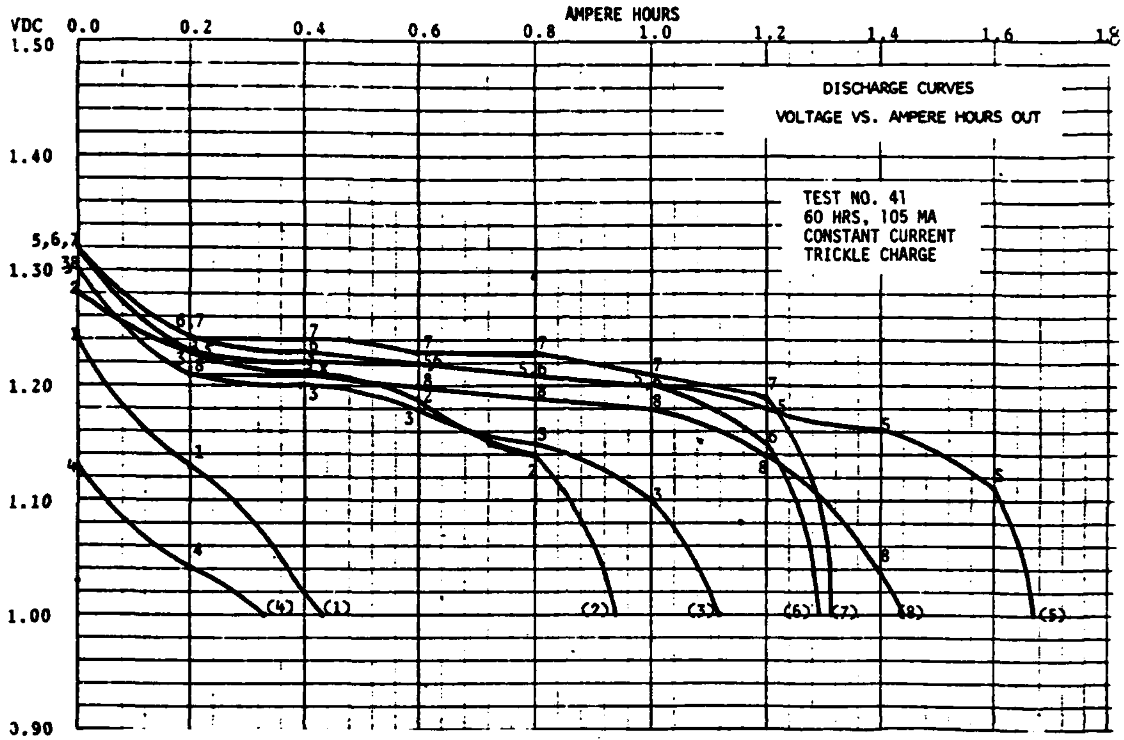


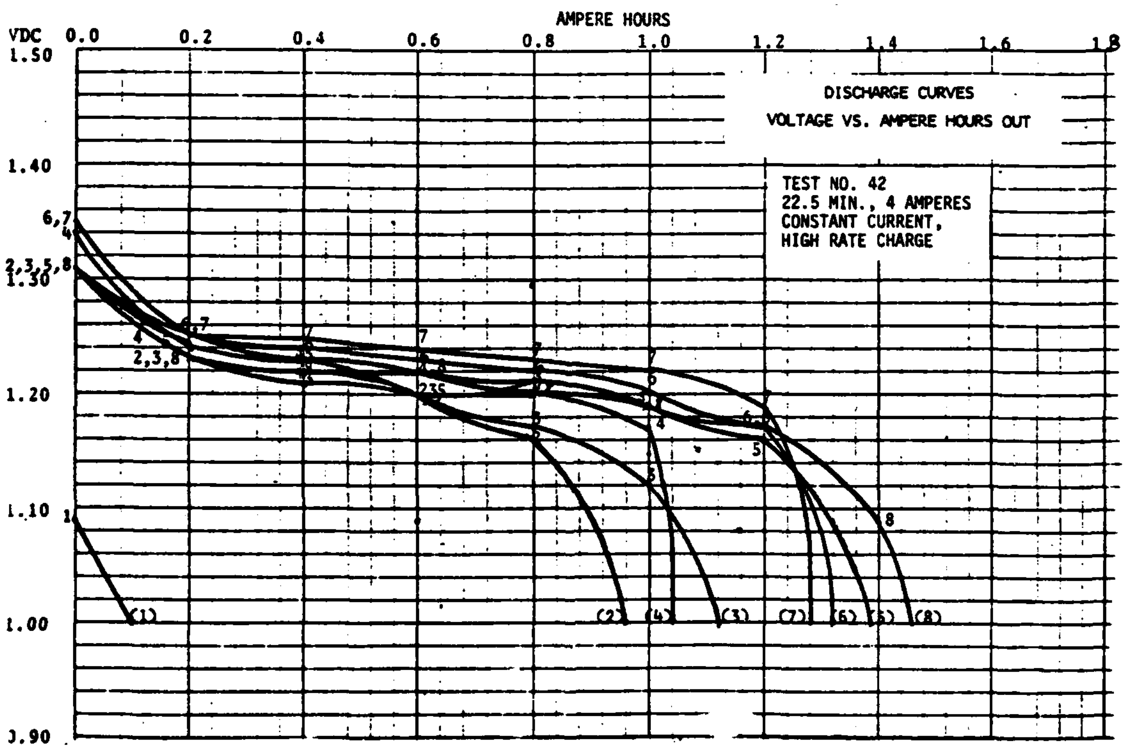
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



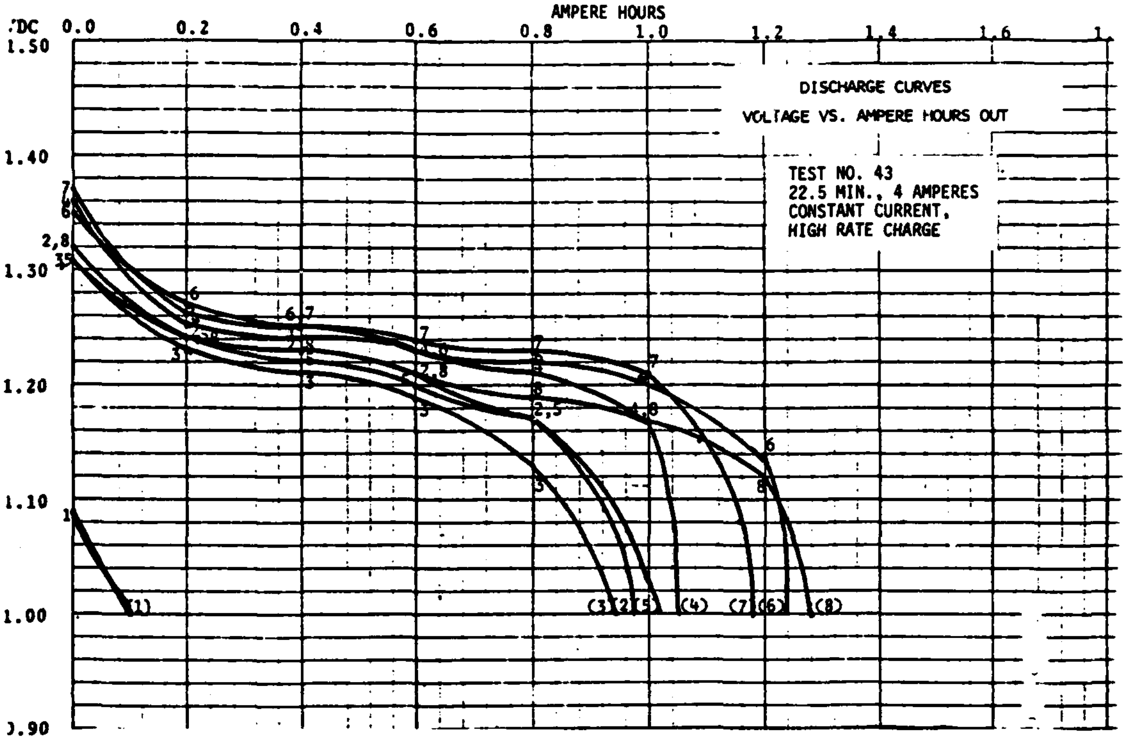


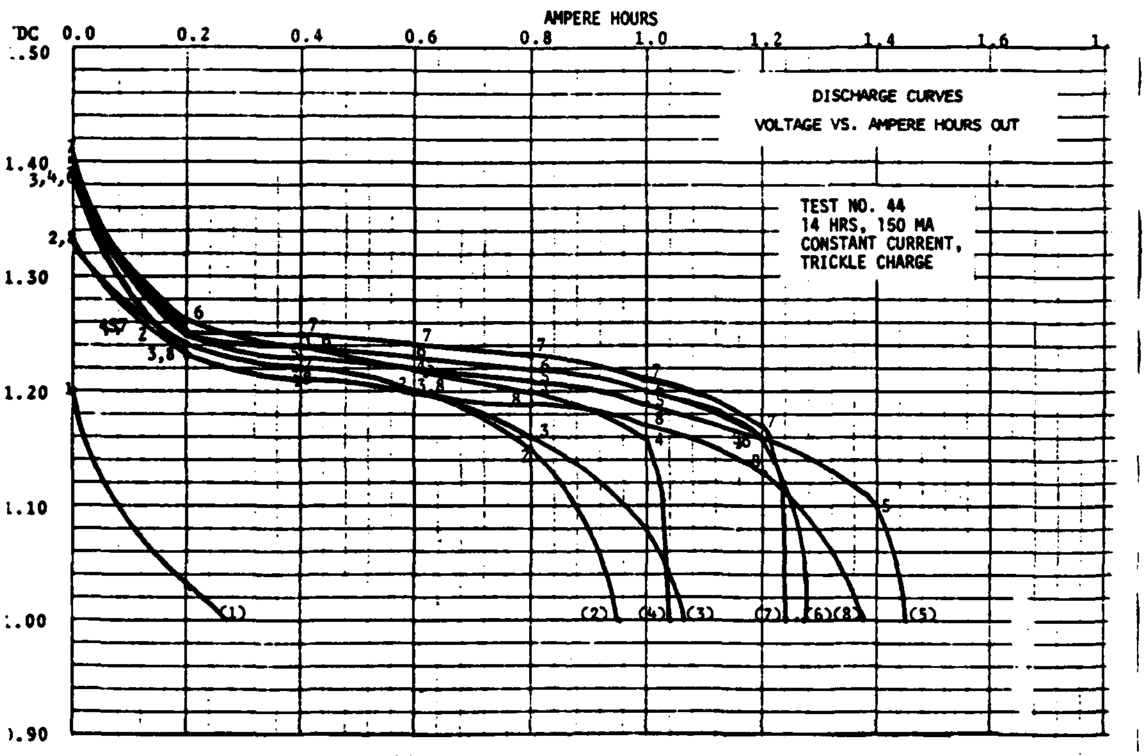
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANAHICA
6 - SANYO
7 - GOULD
8 - HITANICA



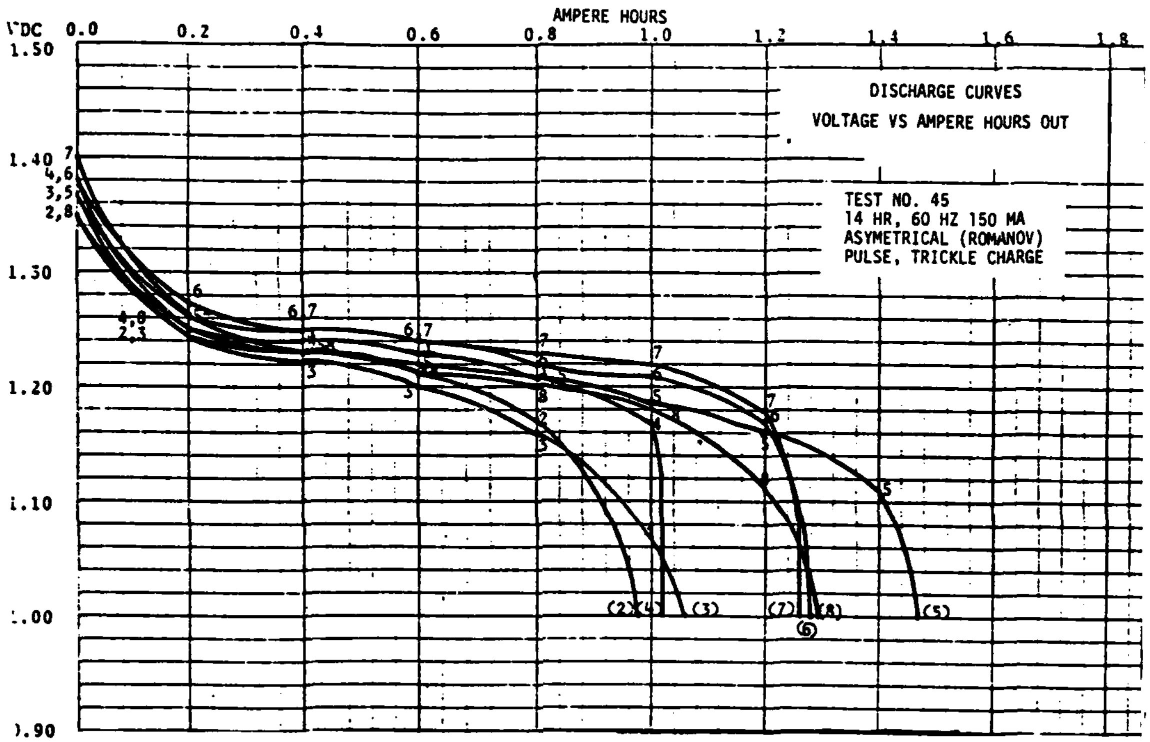


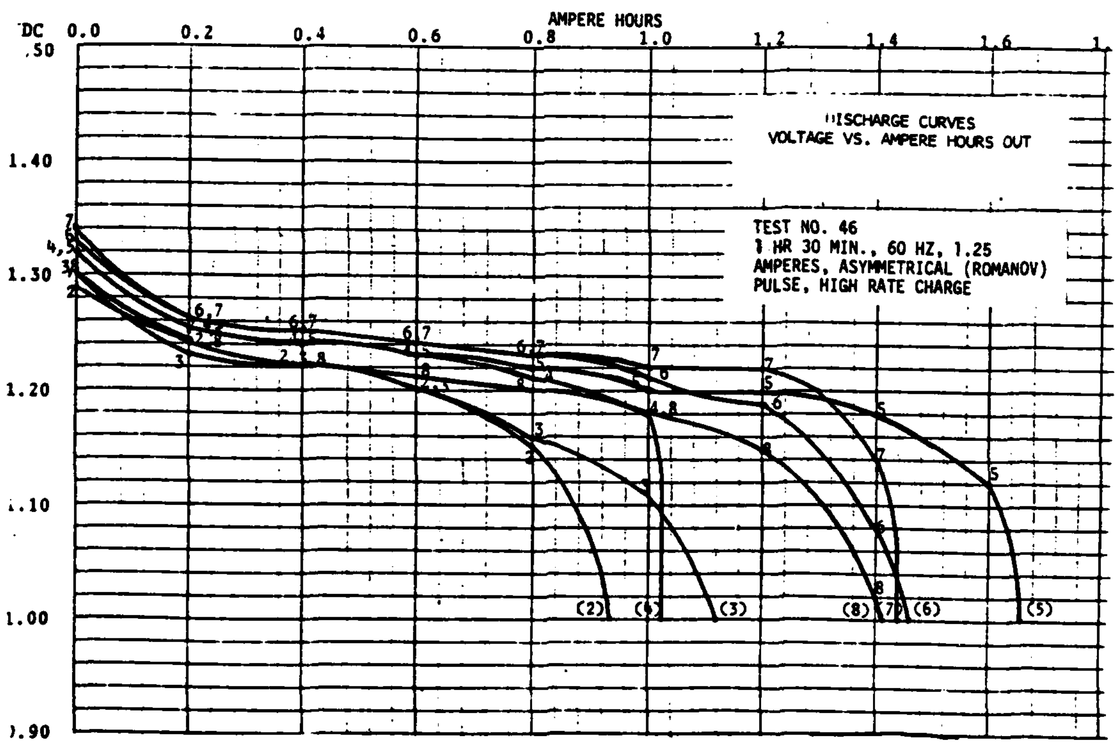
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD
8 - HITANICA



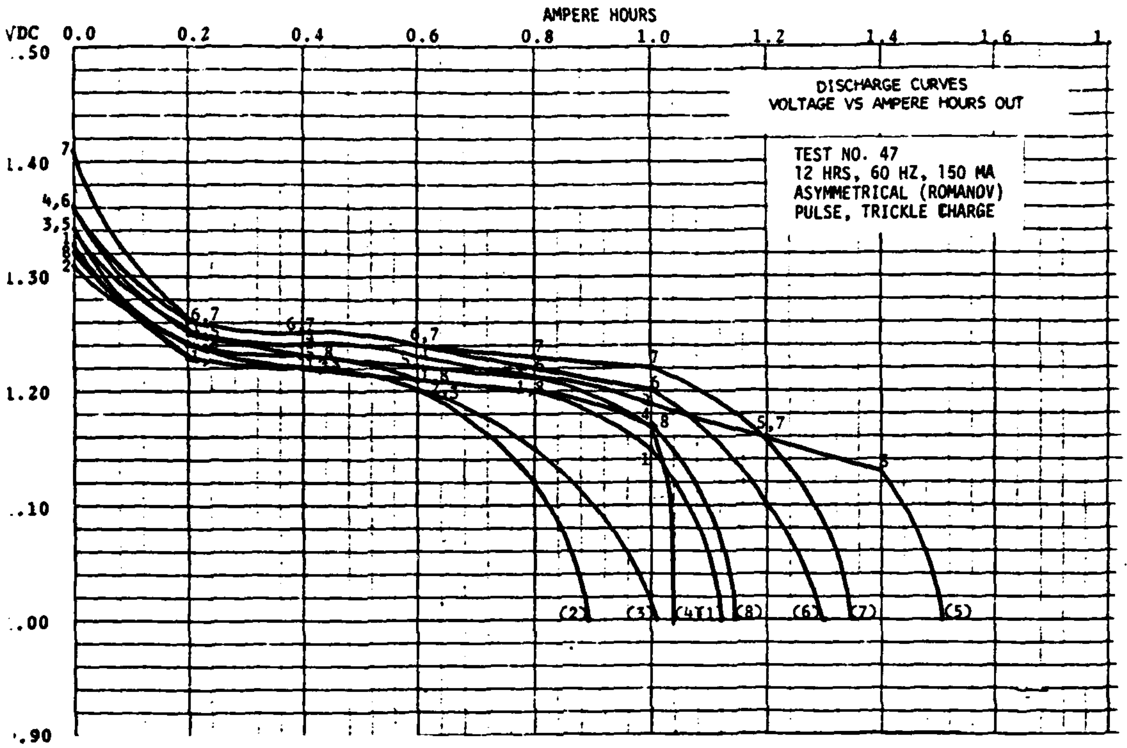


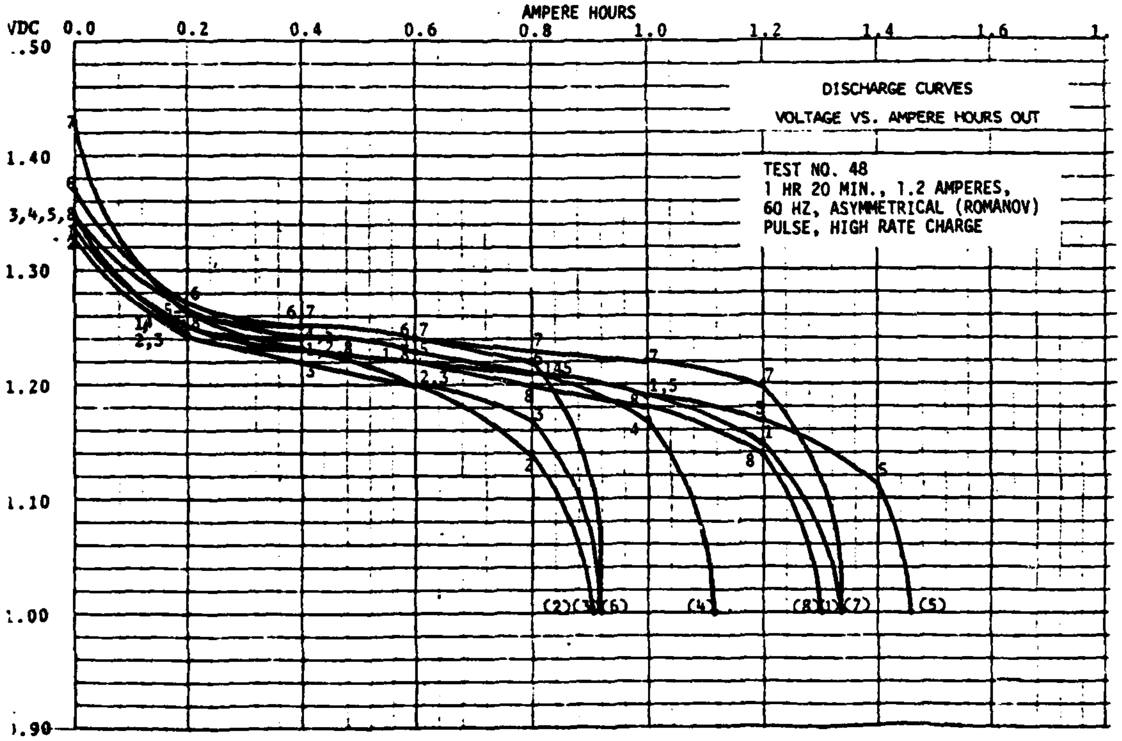
1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD
8 - HITANICA



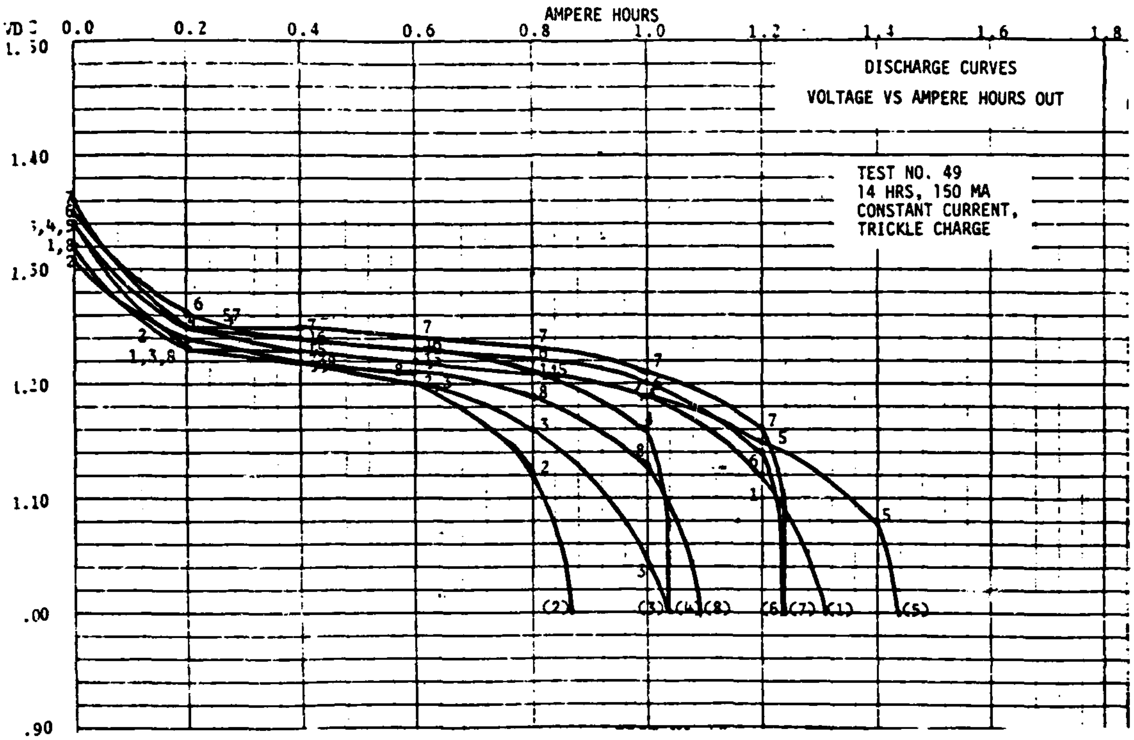


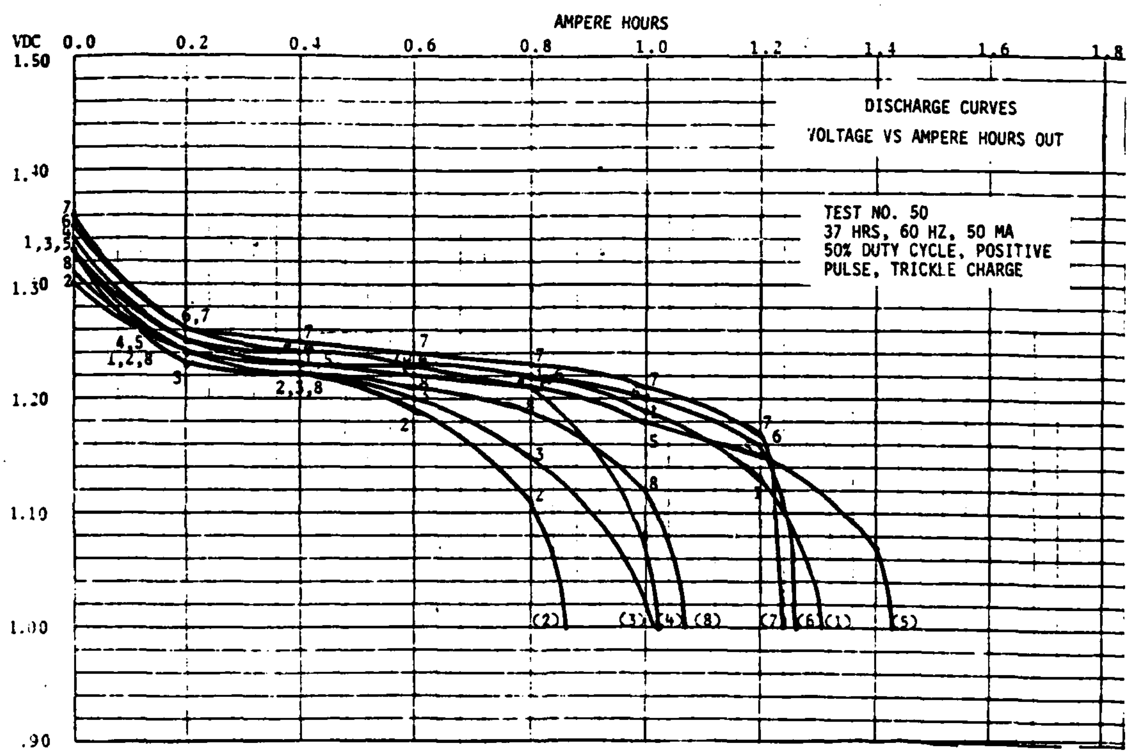
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD
8 - HITANIC





1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E. 8 - HITANICA





1 - MARATHON
2 - SAFT (BUTT)
3 - SAFT (LUG)
4 - G.E.
5 - PANANICA
6 - SANYO
7 - GOULD
8 - HITANIC

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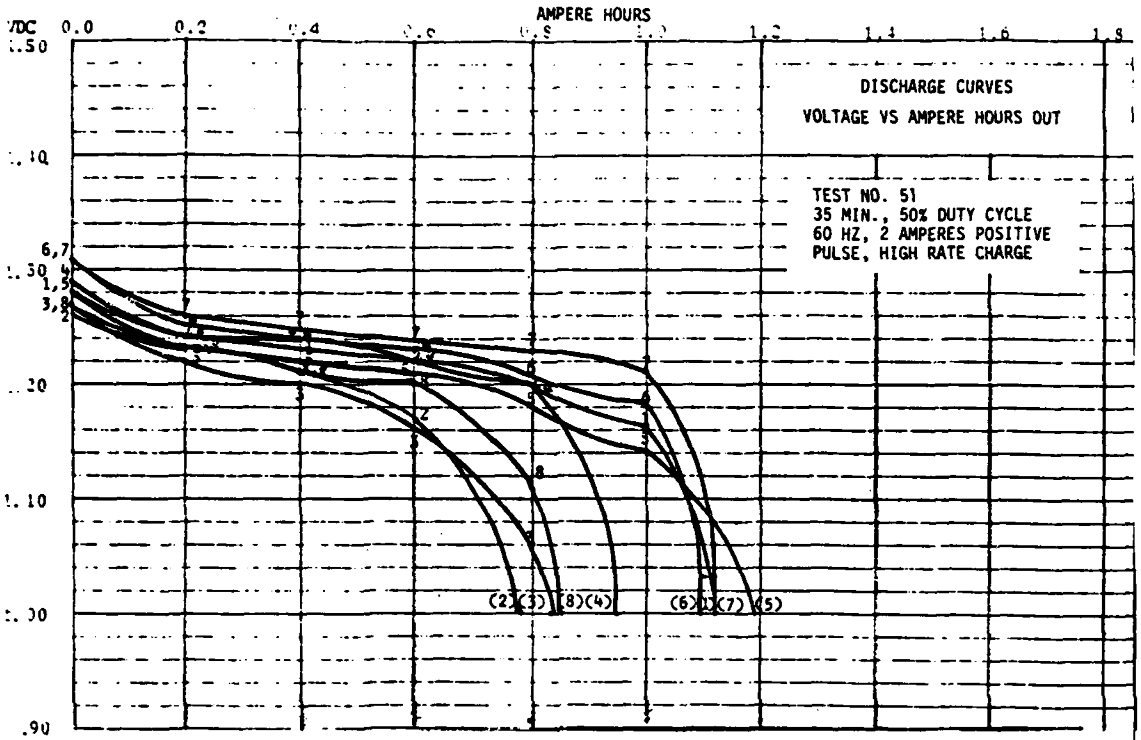
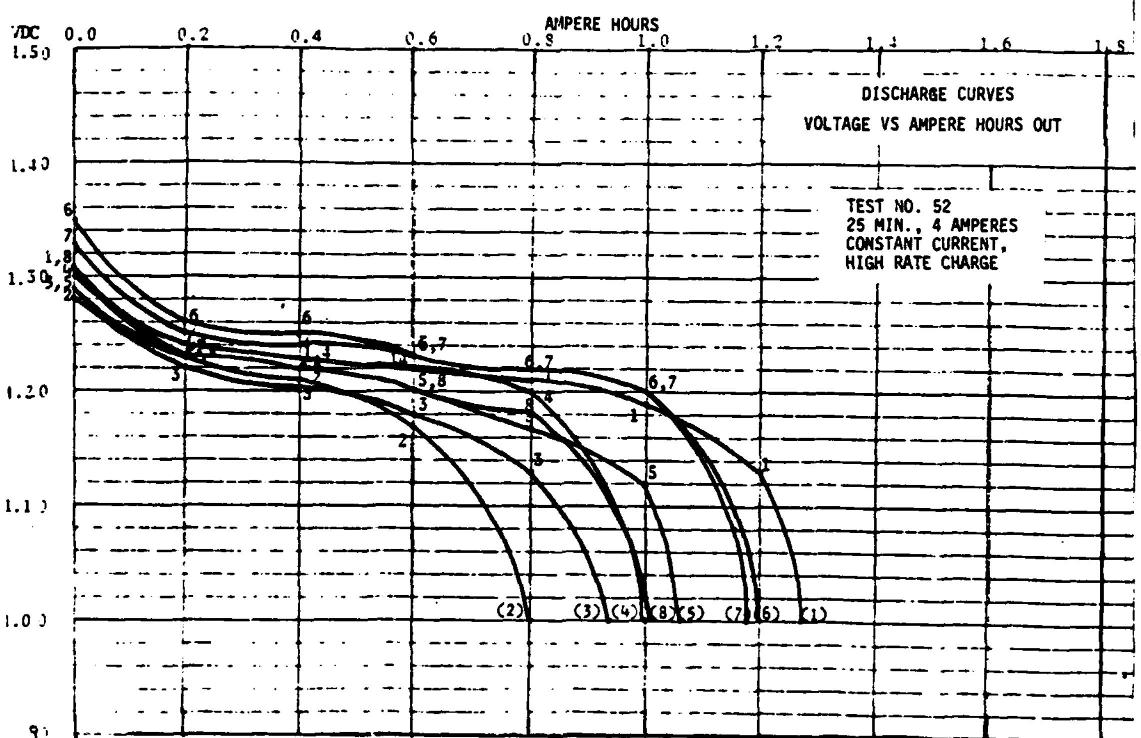
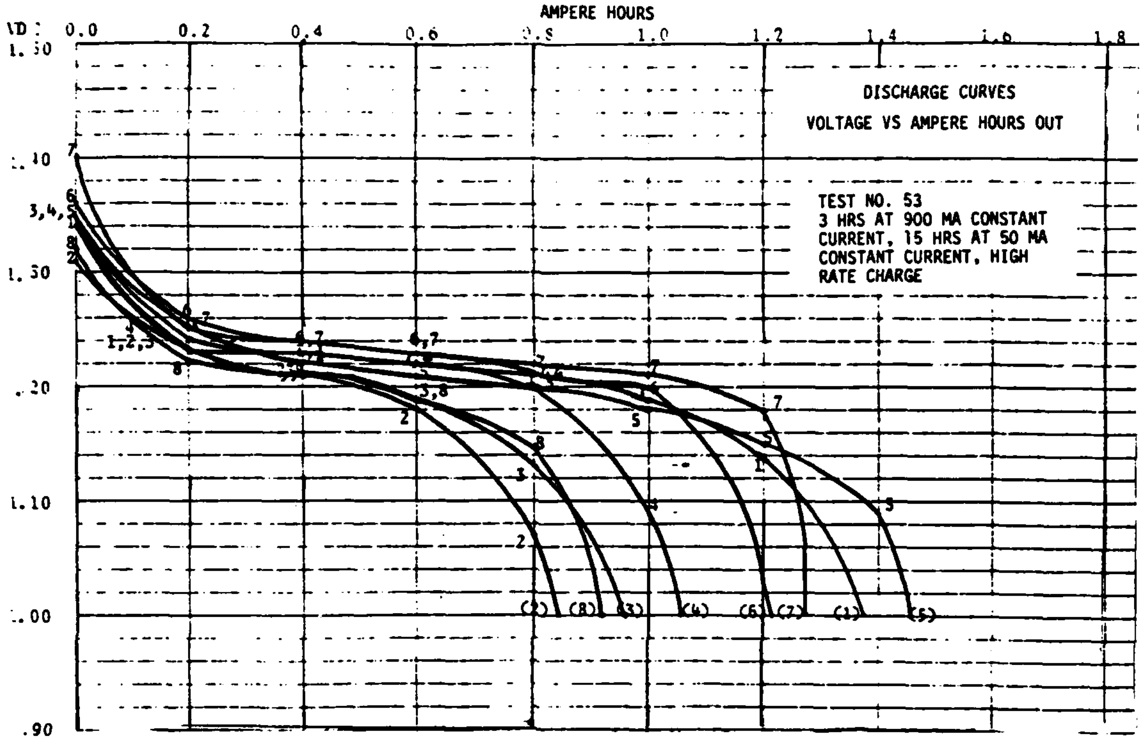
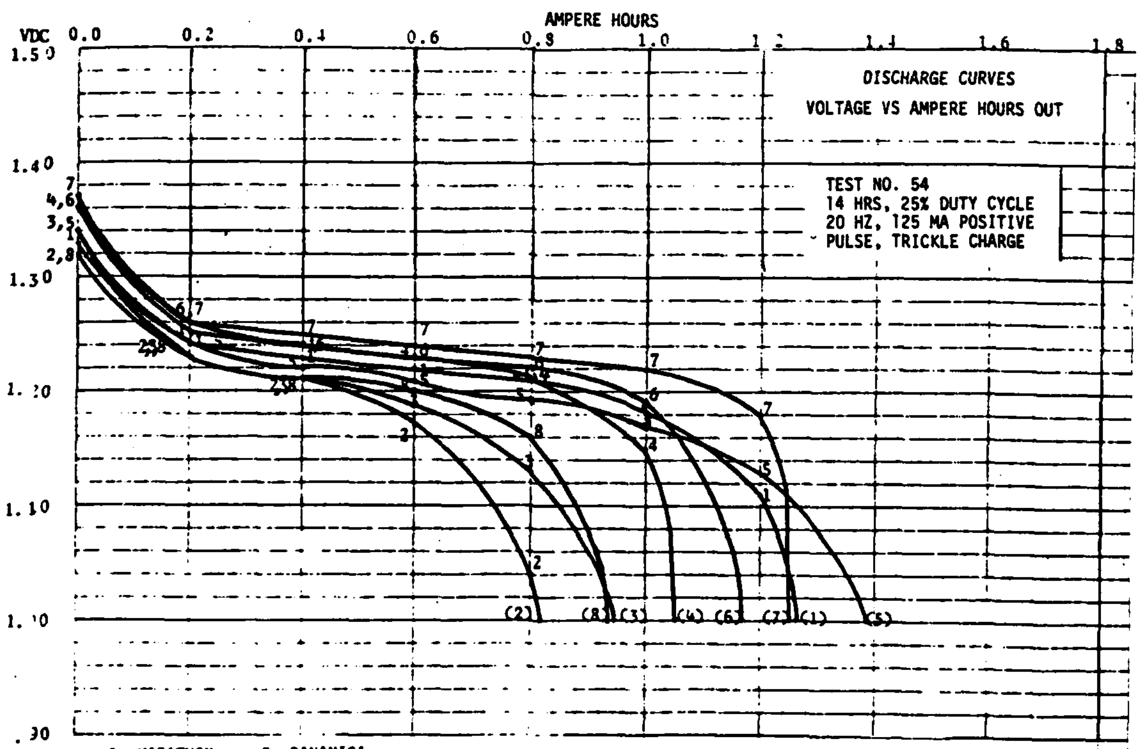


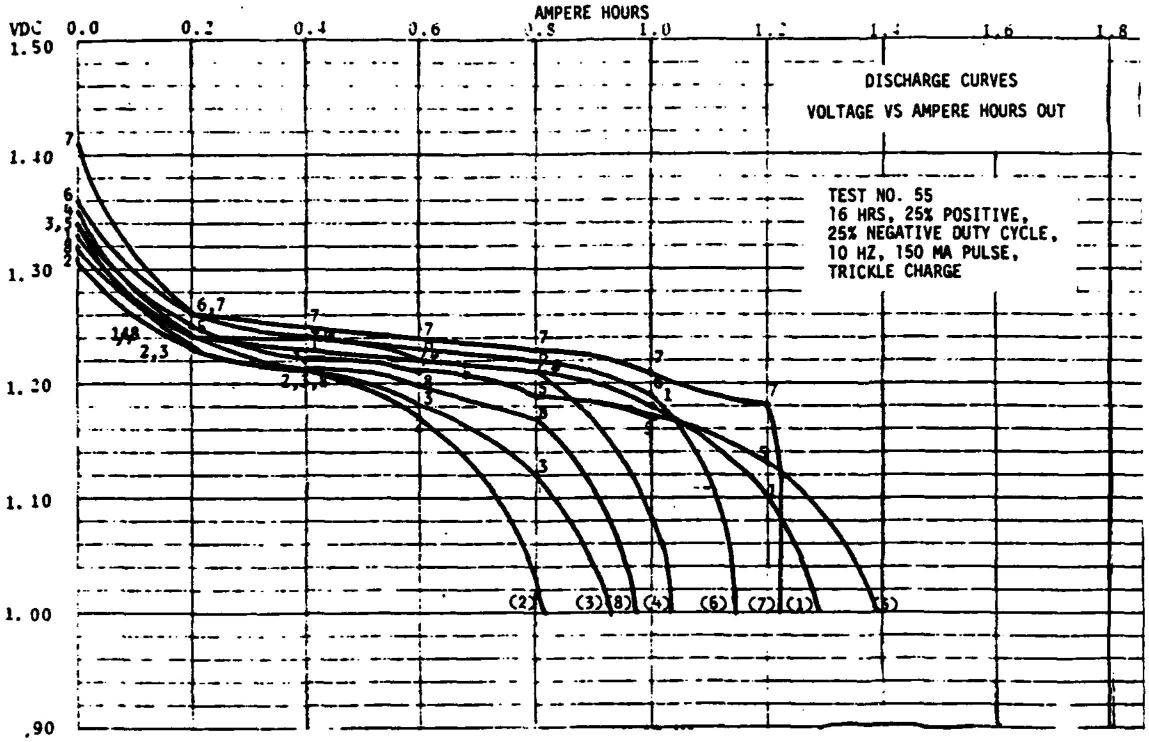


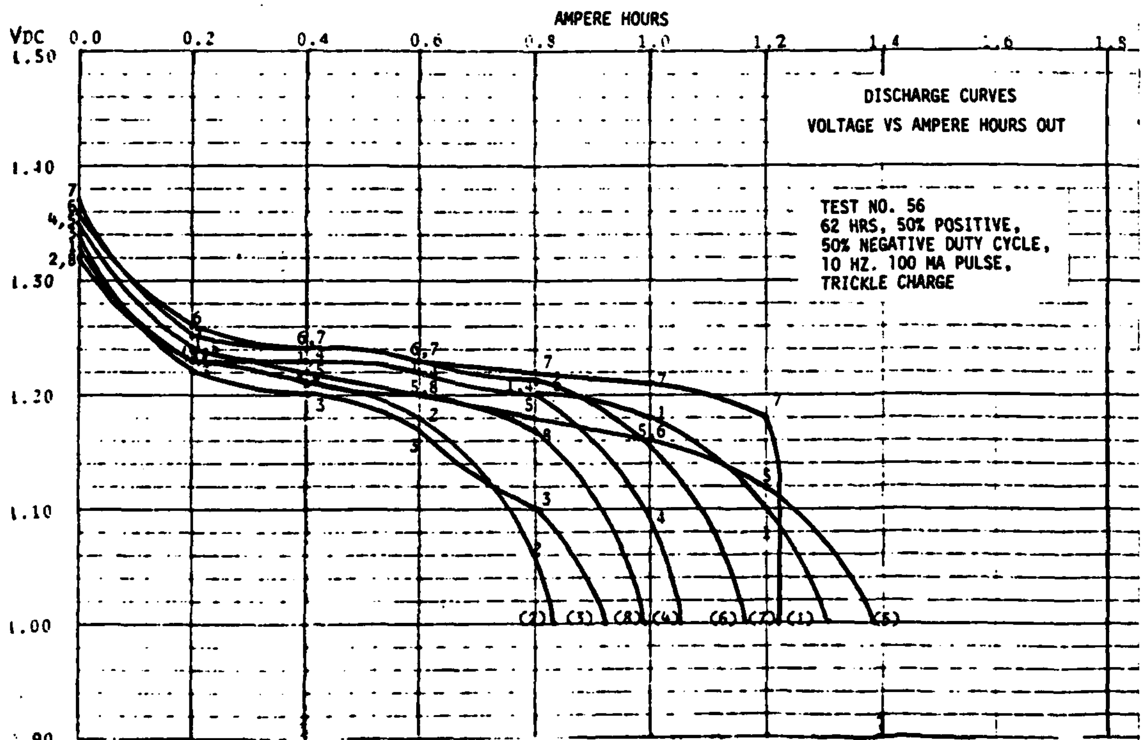
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



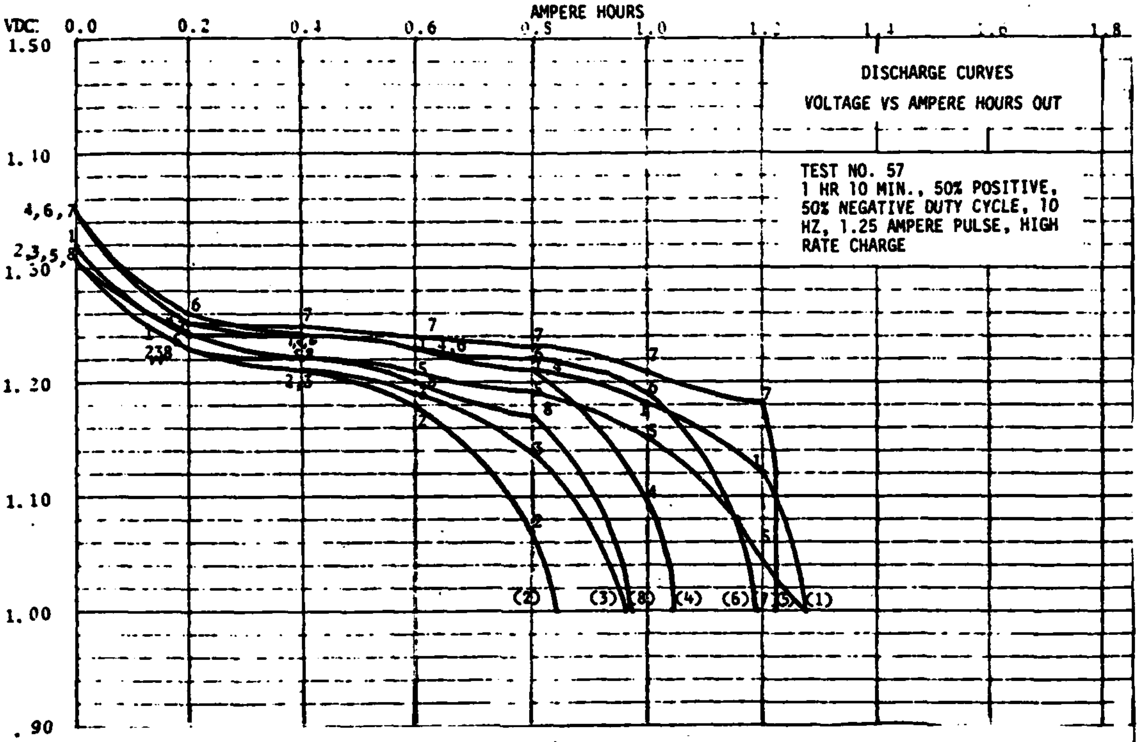


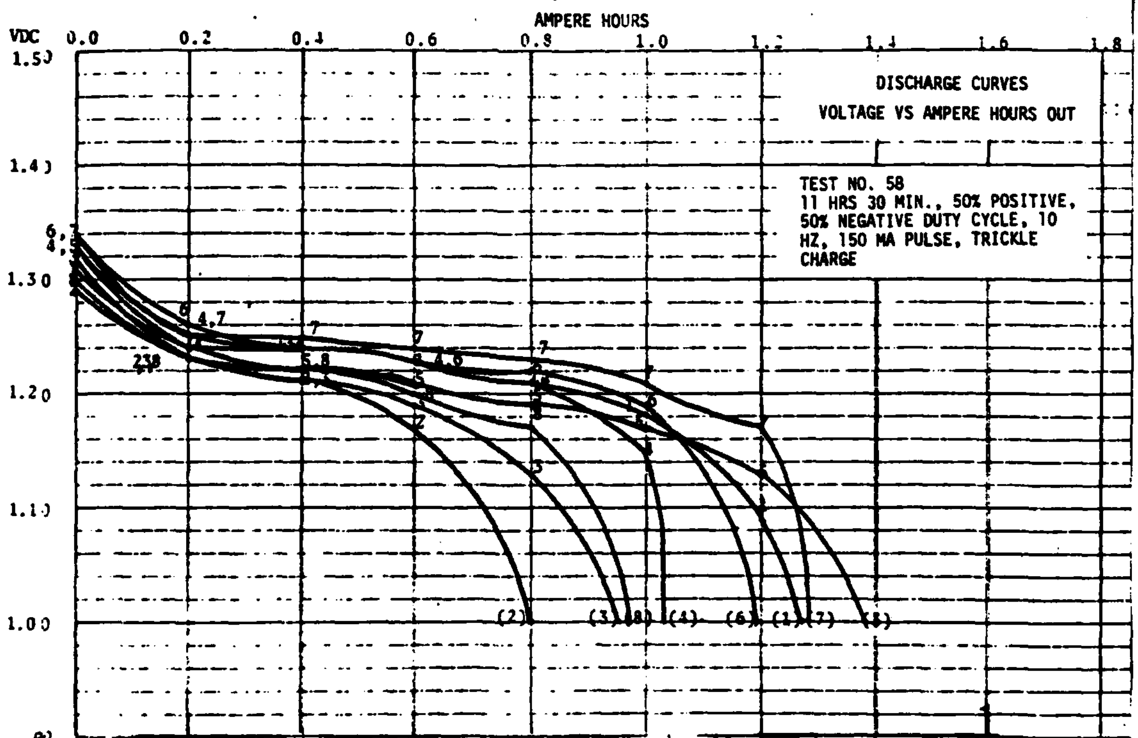
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



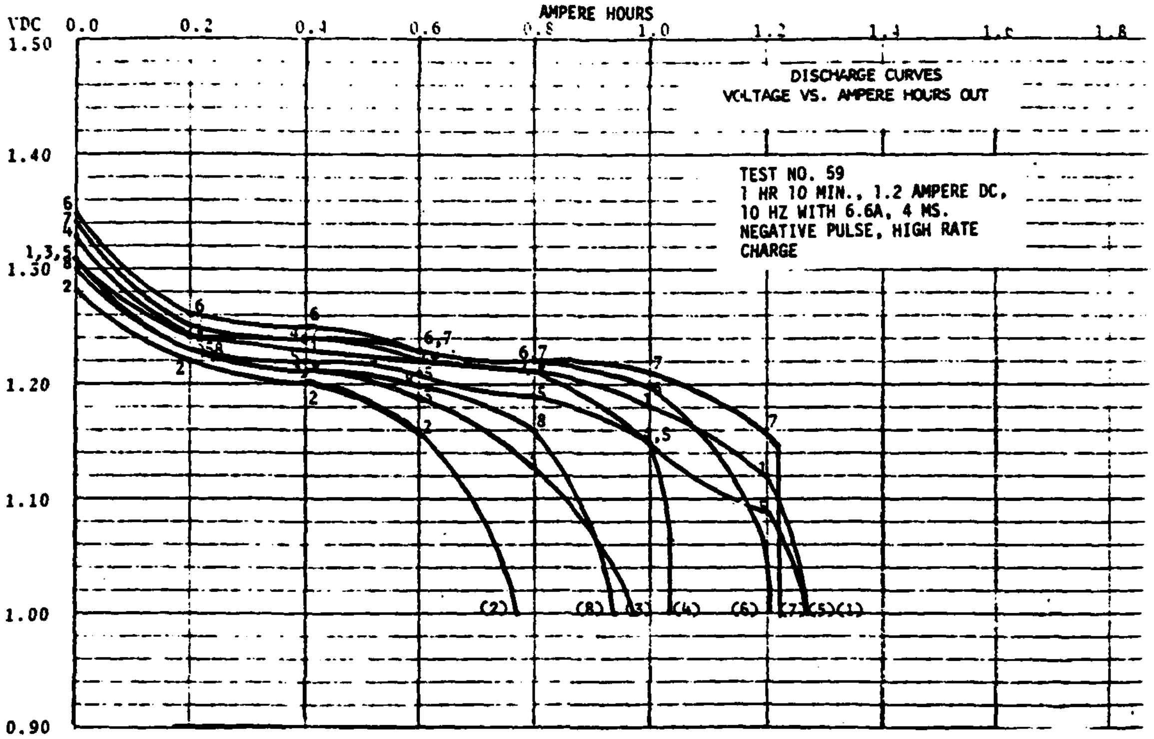


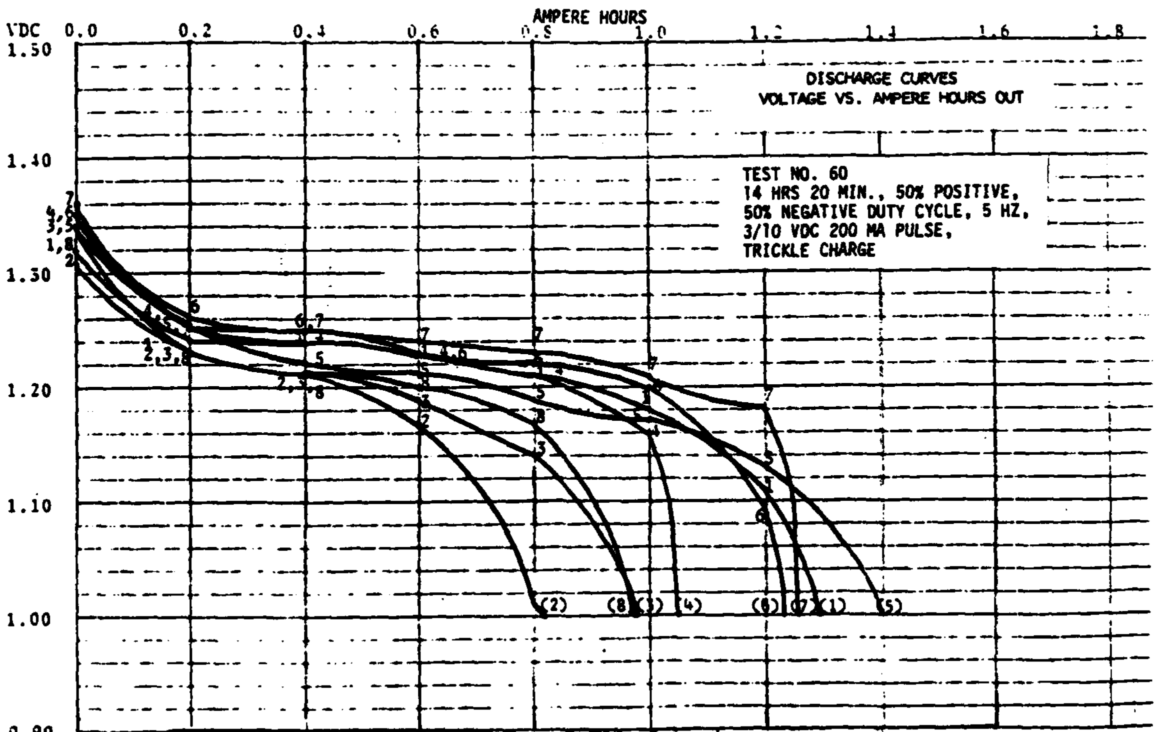
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



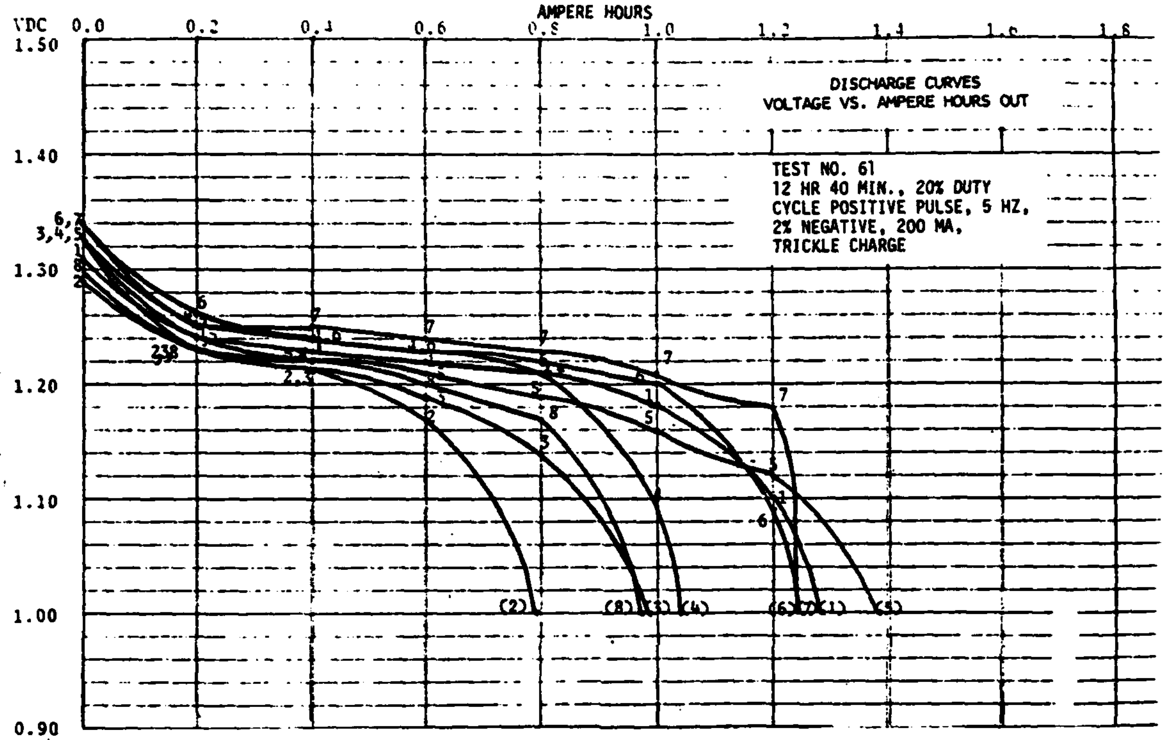


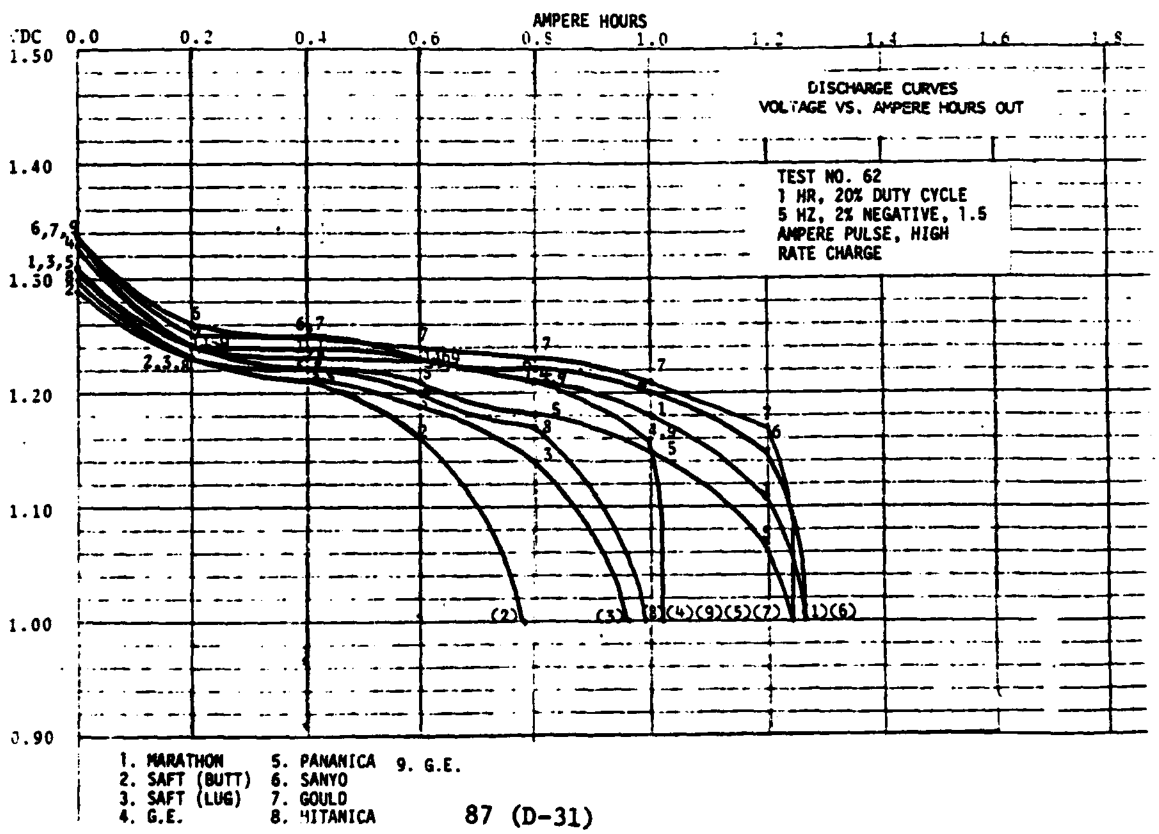
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

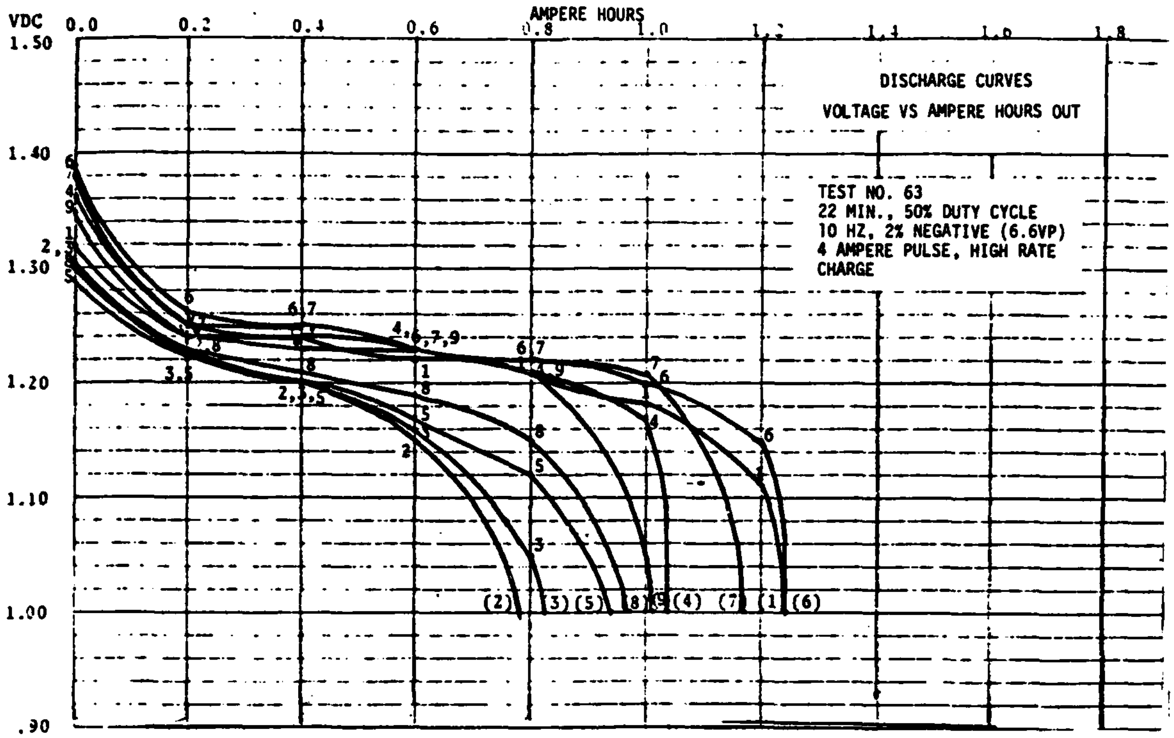


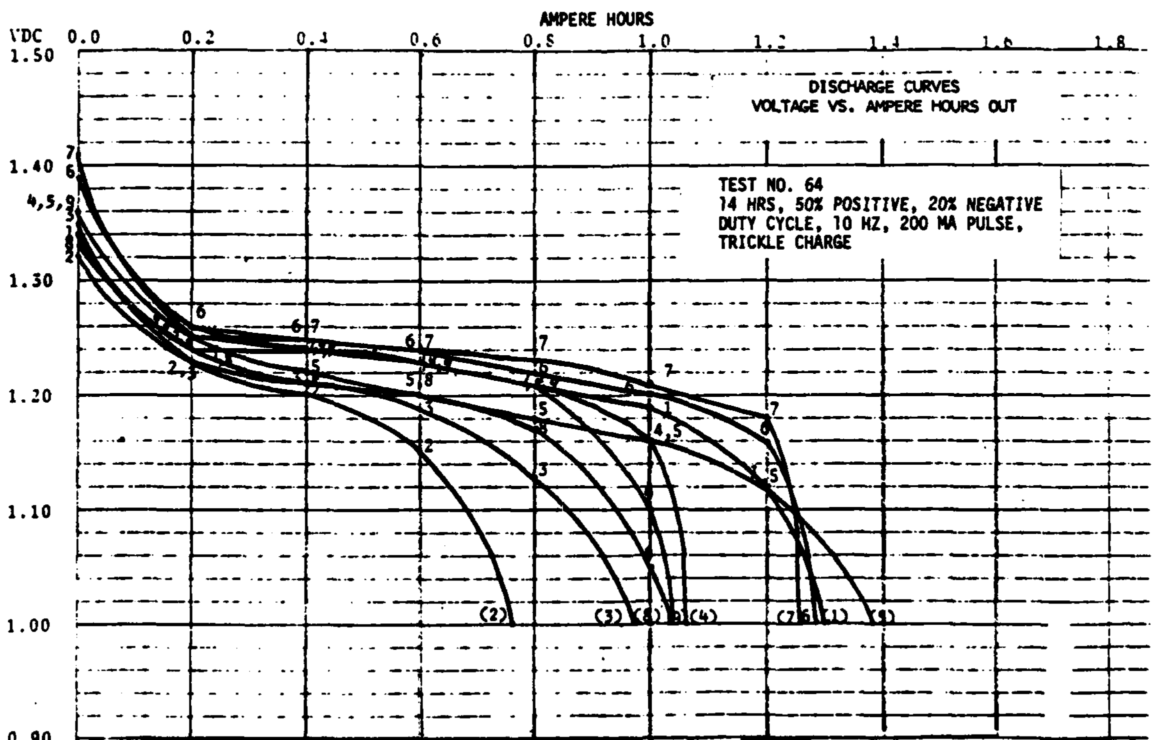


1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

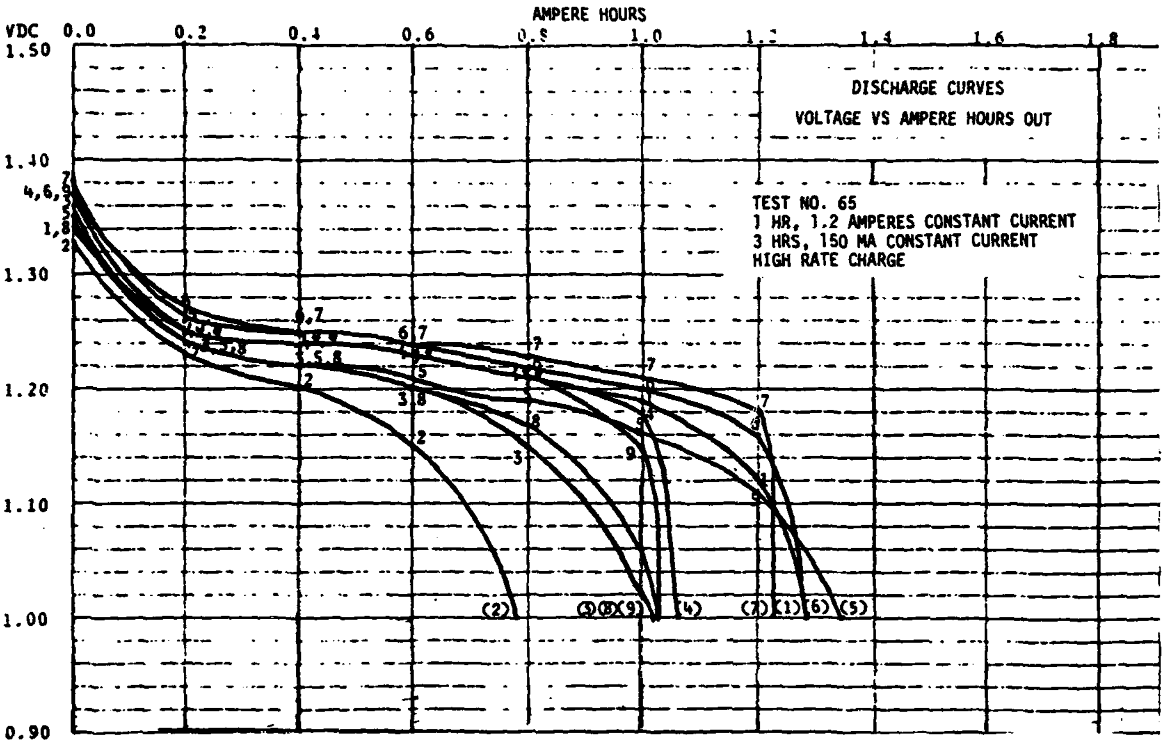

AMPERE HOURS
VDC
DISCHARGE CURVES
VOLTAGE VS. AMPERE HOURS OUT
TEST NO. 61
12 HR 40 MIN., 20% DUTY
CYCLE POSITIVE PULSE, 5 HZ,
2% NEGATIVE, 200 MA,
TRICKLE CHARGE

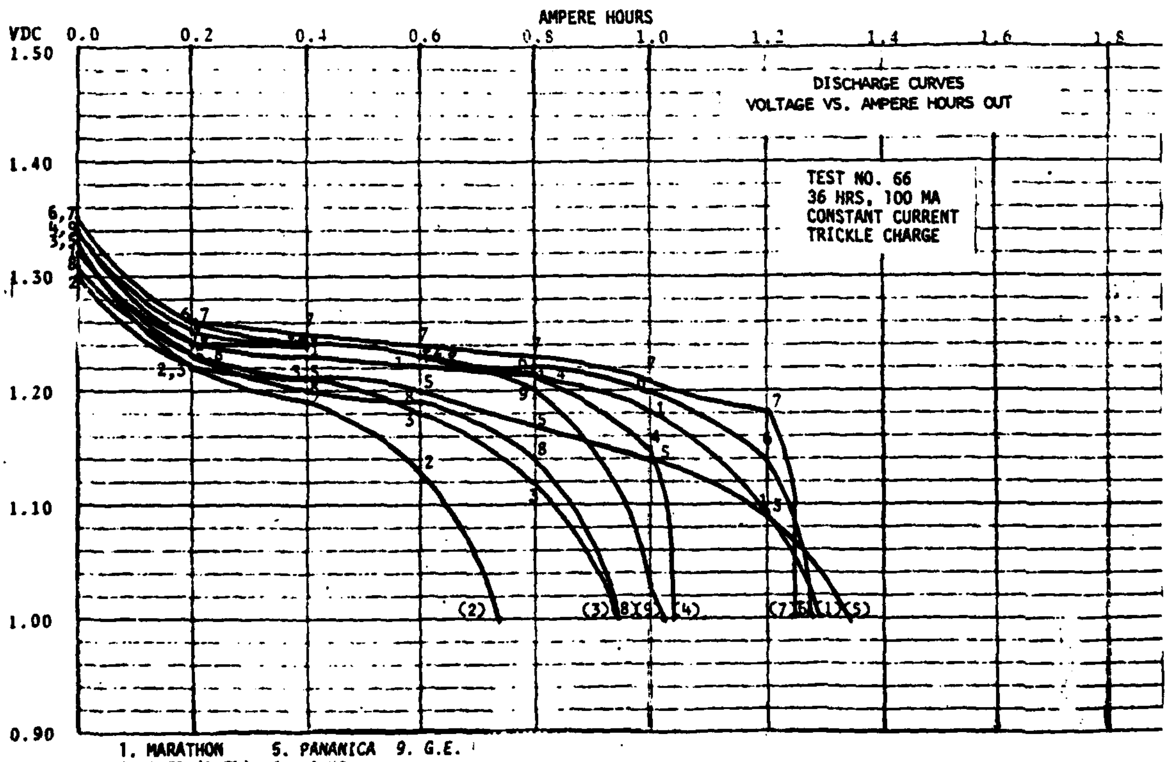

AMPERE HOURS
VDC
DISCHARGE CURVES
VOLTAGE VS. AMPERE HOURS OUT
TEST NO. 62
1 HR, 20% DUTY CYCLE
5 HZ, 2% NEGATIVE, 1.5
AMPERE PULSE, HIGH
RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9. G.E.



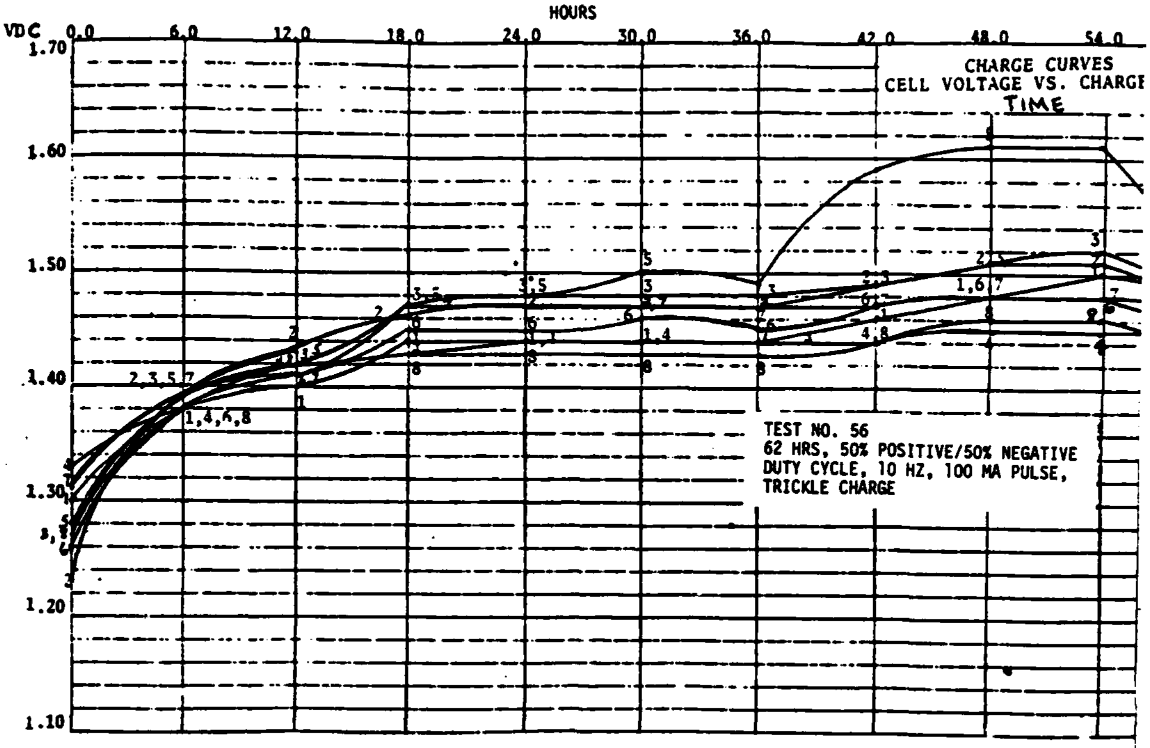


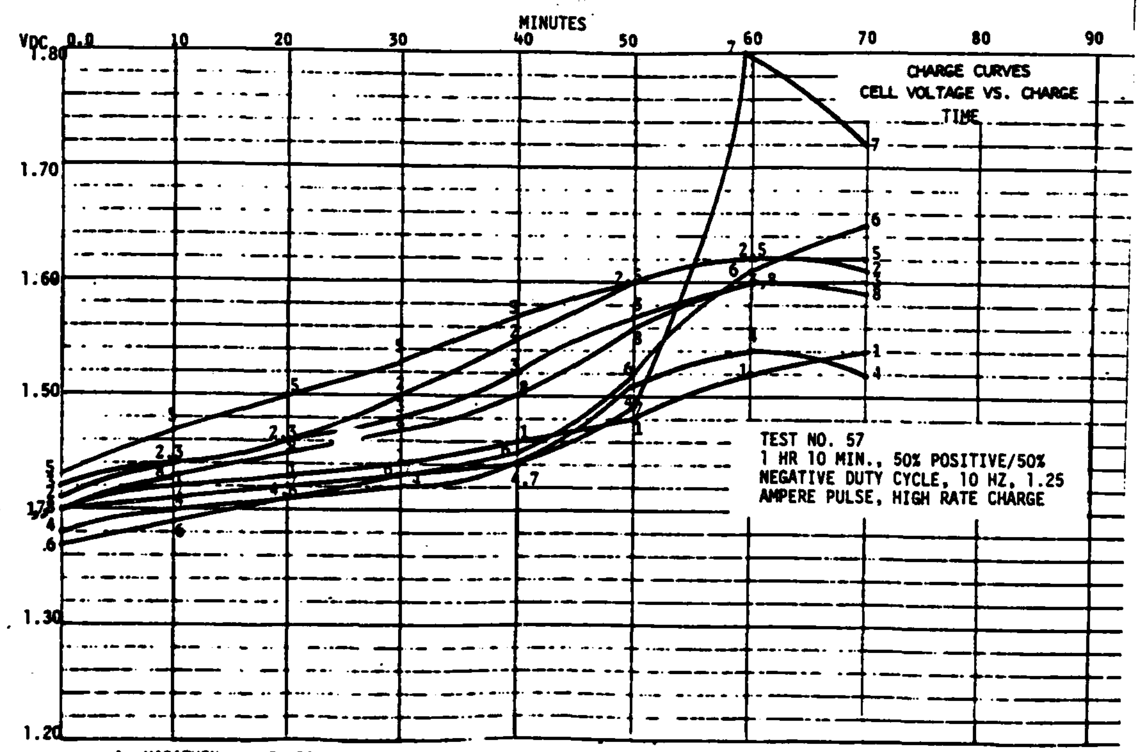
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9. G.E.





1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9. G.E.





1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA

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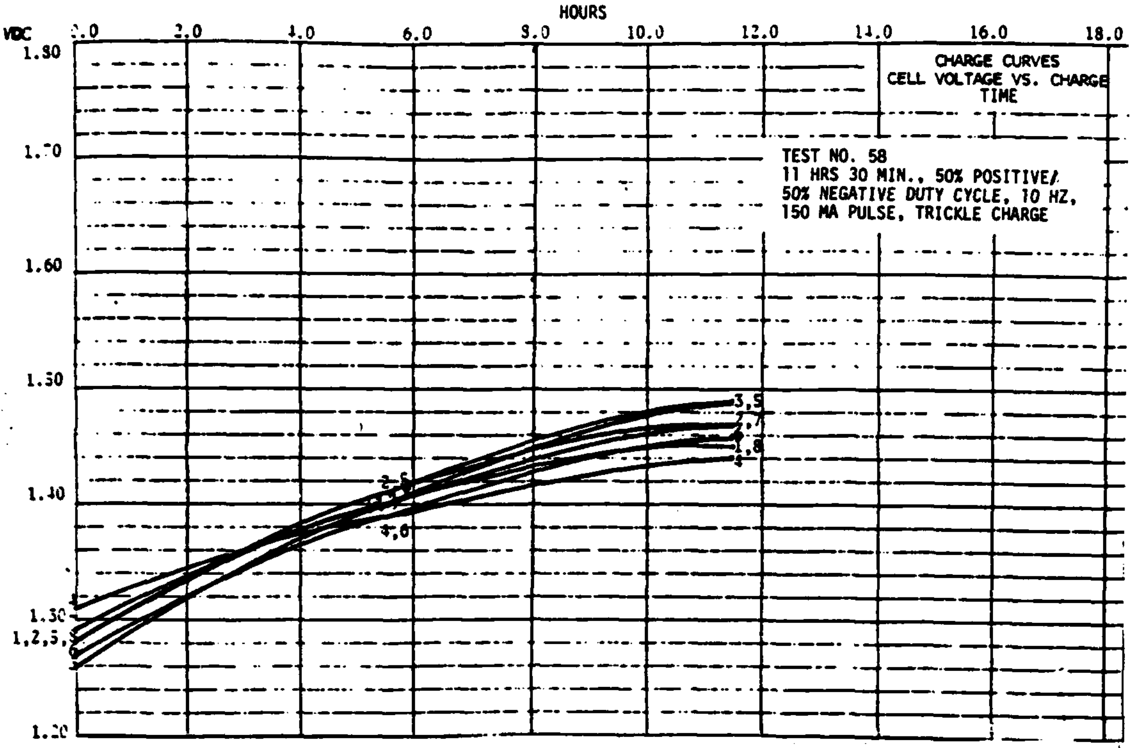
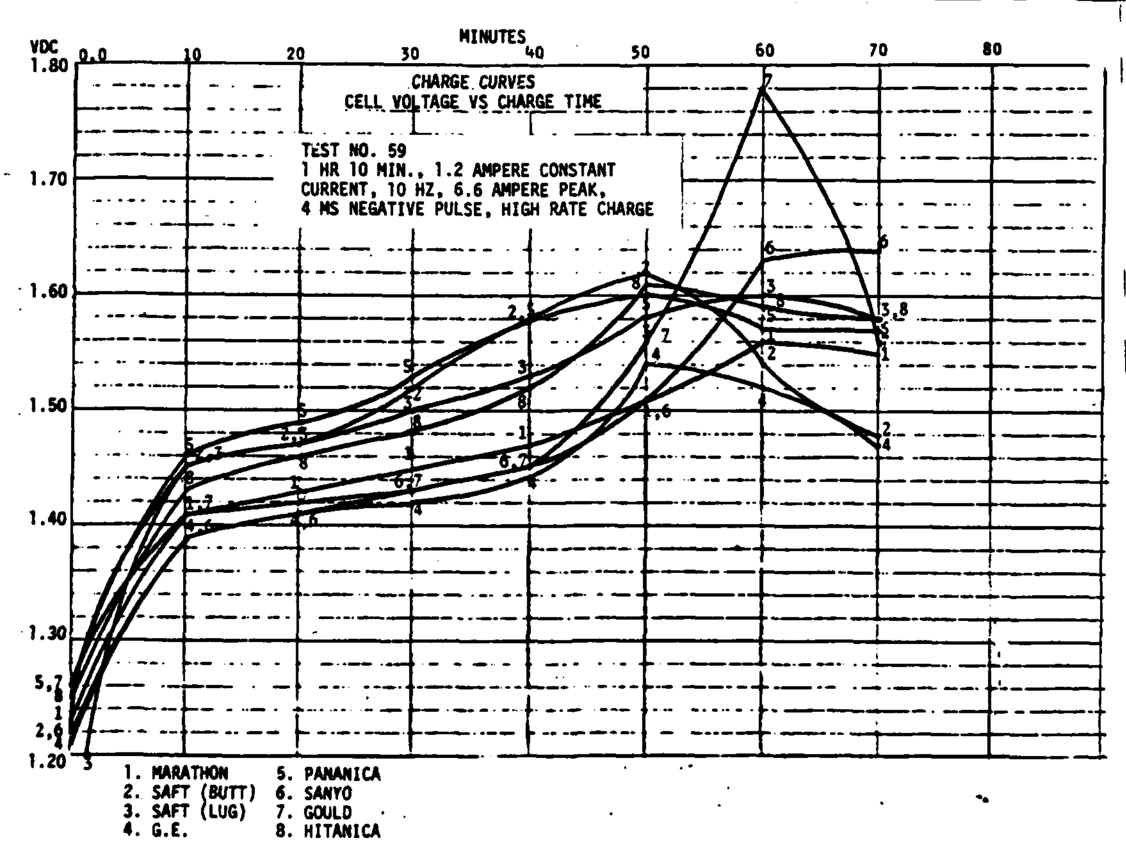
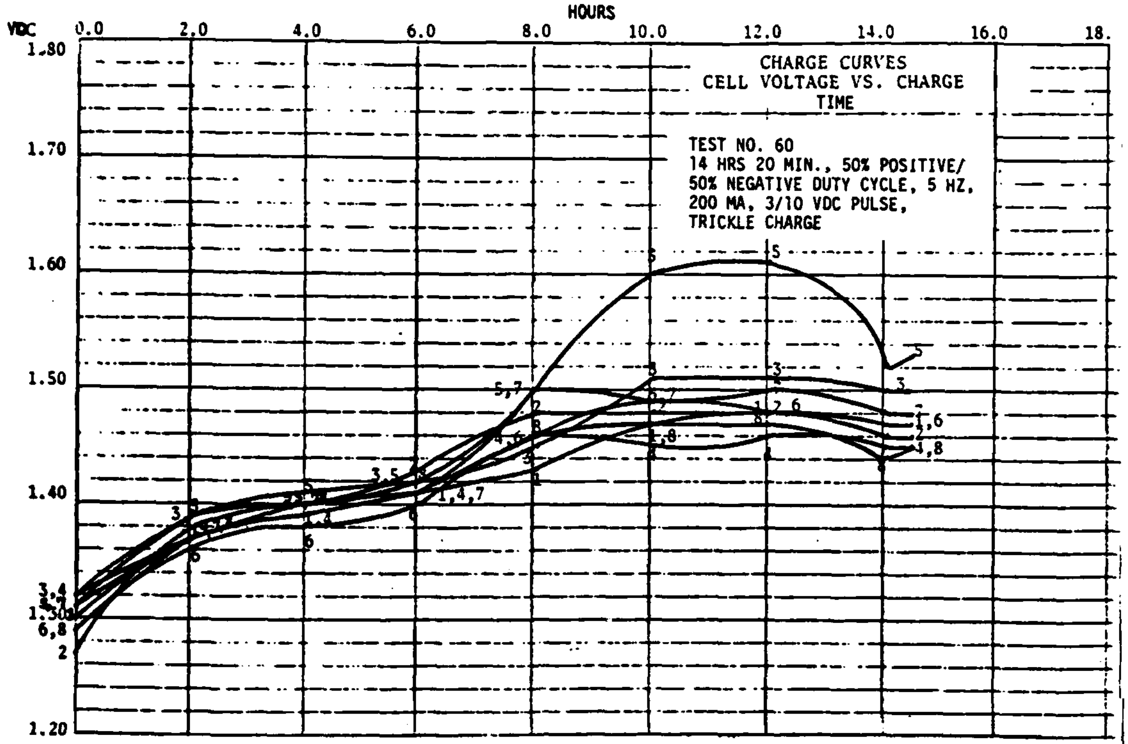
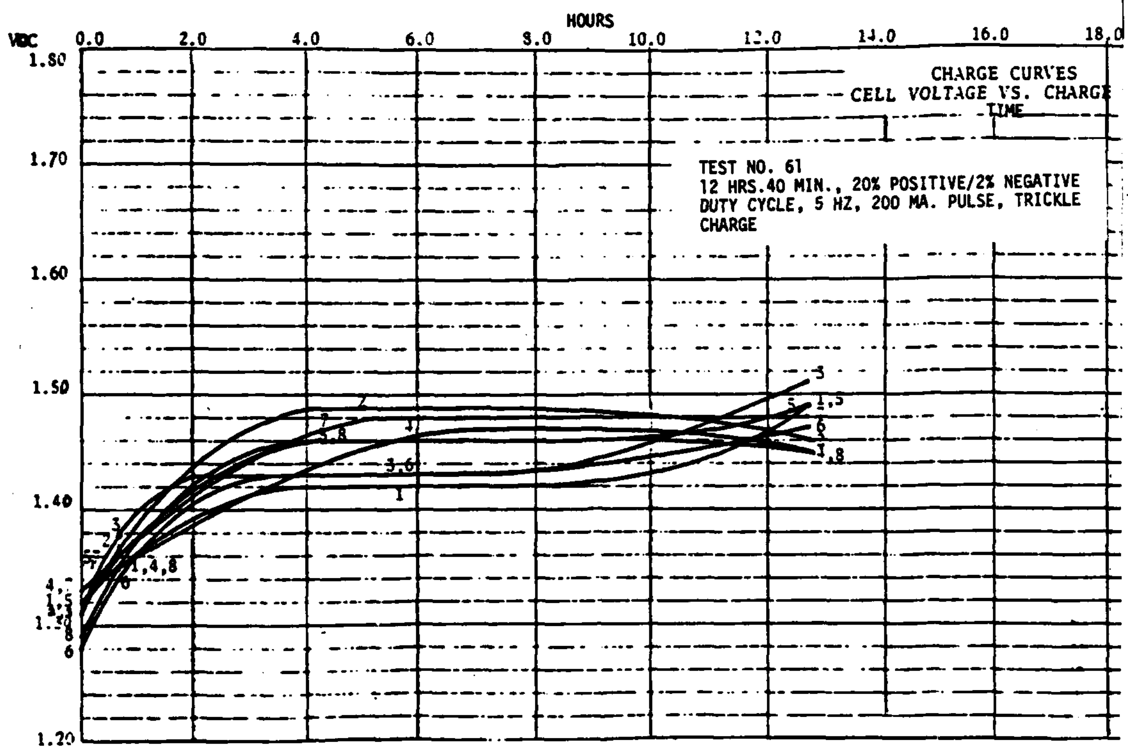
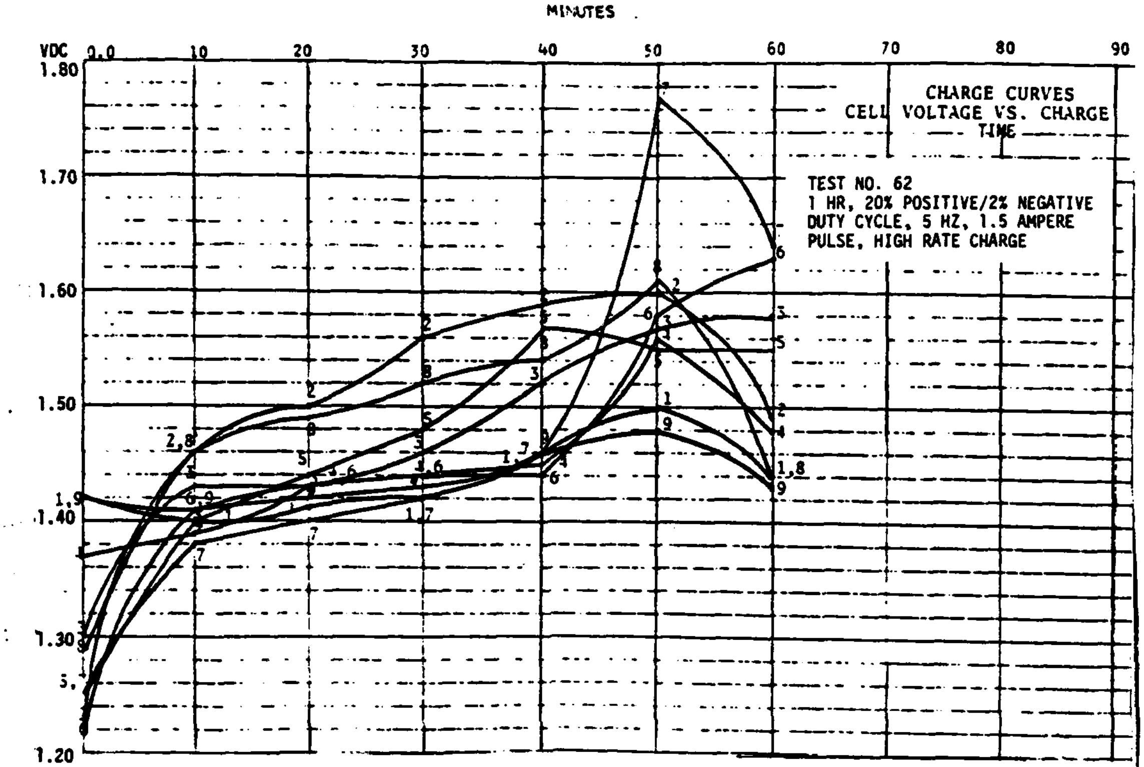

HOURS
VDC
CHARGE CURVES
CELL VOLTAGE VS. CHARGE TIME
TEST NO. 58
11 HRS 30 MIN., 50% POSITIVE/
50% NEGATIVE DUTY CYCLE, 10 HZ,
150 MA PULSE, TRICKLE CHARGE

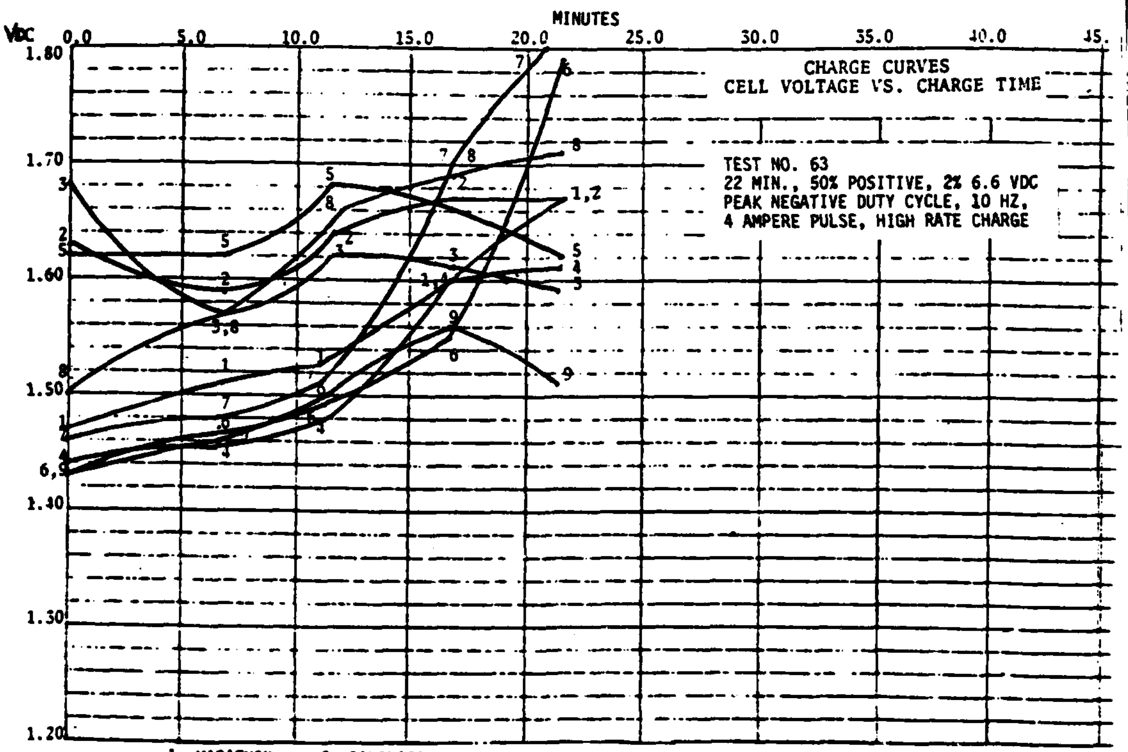

MINUTES
VDC
CHARGE CURVES
CELL VOLTAGE VS CHARGE TIME
TEST NO. 59
1 HR 10 MIN., 1.2 AMPERE CONSTANT
CURRENT, 10 HZ, 6.6 AMPERE PEAK,
4 MS NEGATIVE PULSE, HIGH RATE CHARGE
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA



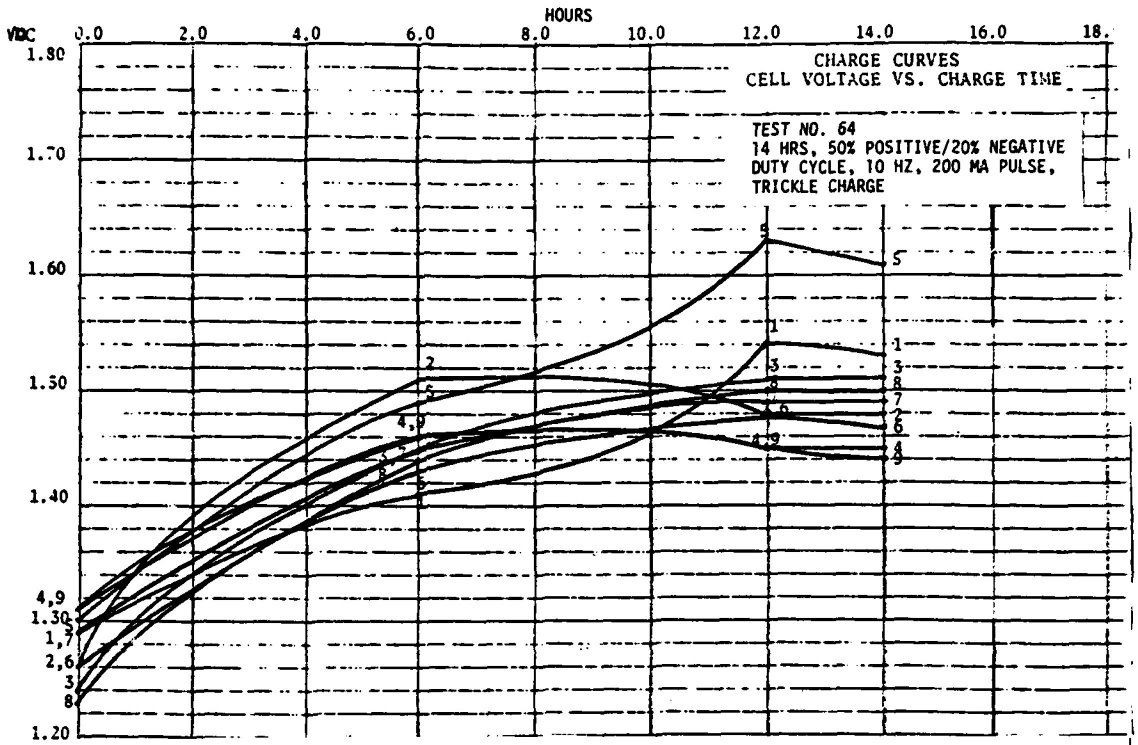


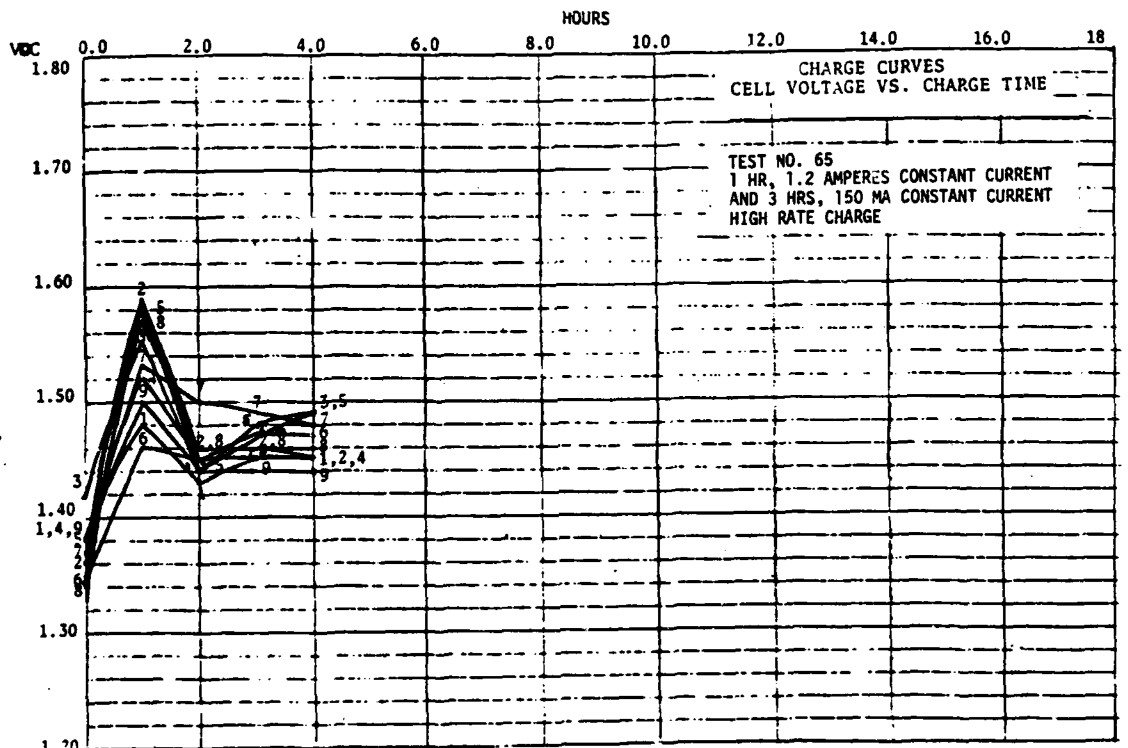
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA





1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9 - G.E.





1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD
8. HITANICA
9 - G.E.

AD-A119 826 FREZZOLINI ELECTRONICS INC HAWTHRONE NJ GENERAL RESEA--ETC F/G 10/3
TECHNICAL INVESTIGATION REPORT: SEALED MINI-NICKEL CADMIUM BATT--ETC(U)
SEP 82 J CRAWFORD, R S PINKHAM N68335-81-C-0502

UNCLASSIFIED NAEC-92-161 NL

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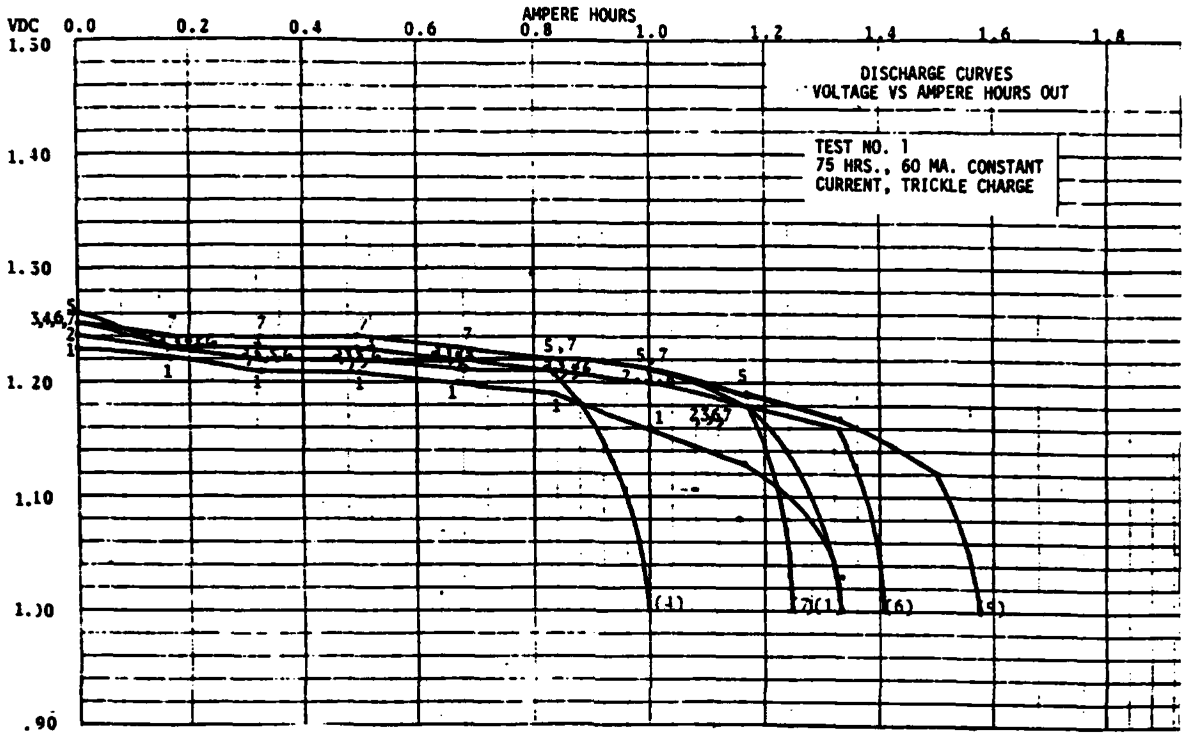
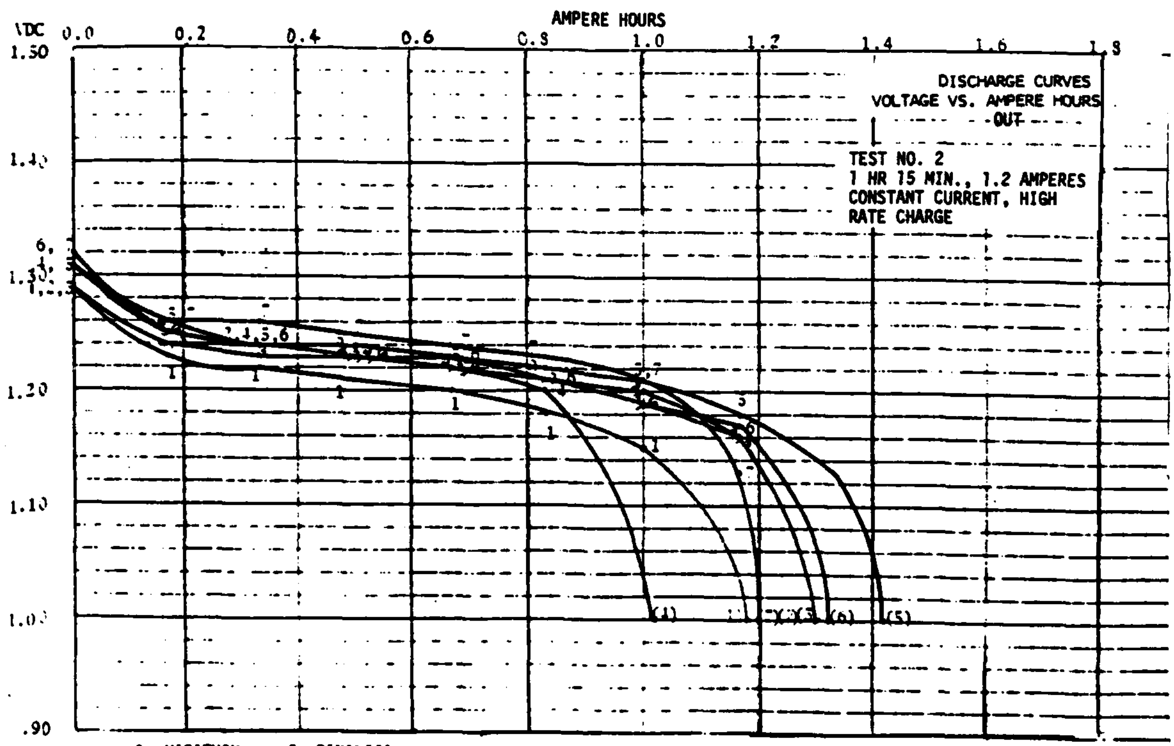
APPENDIX D - CELL DISCHARGE GRAPHS





1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD

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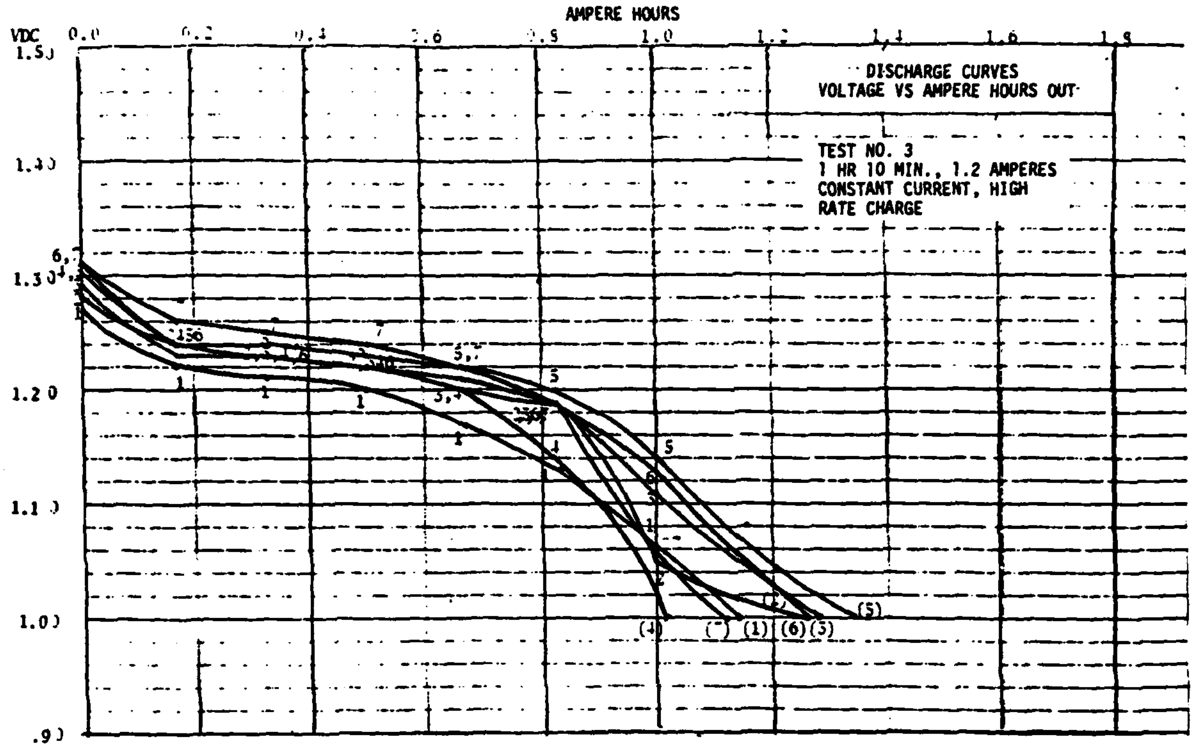
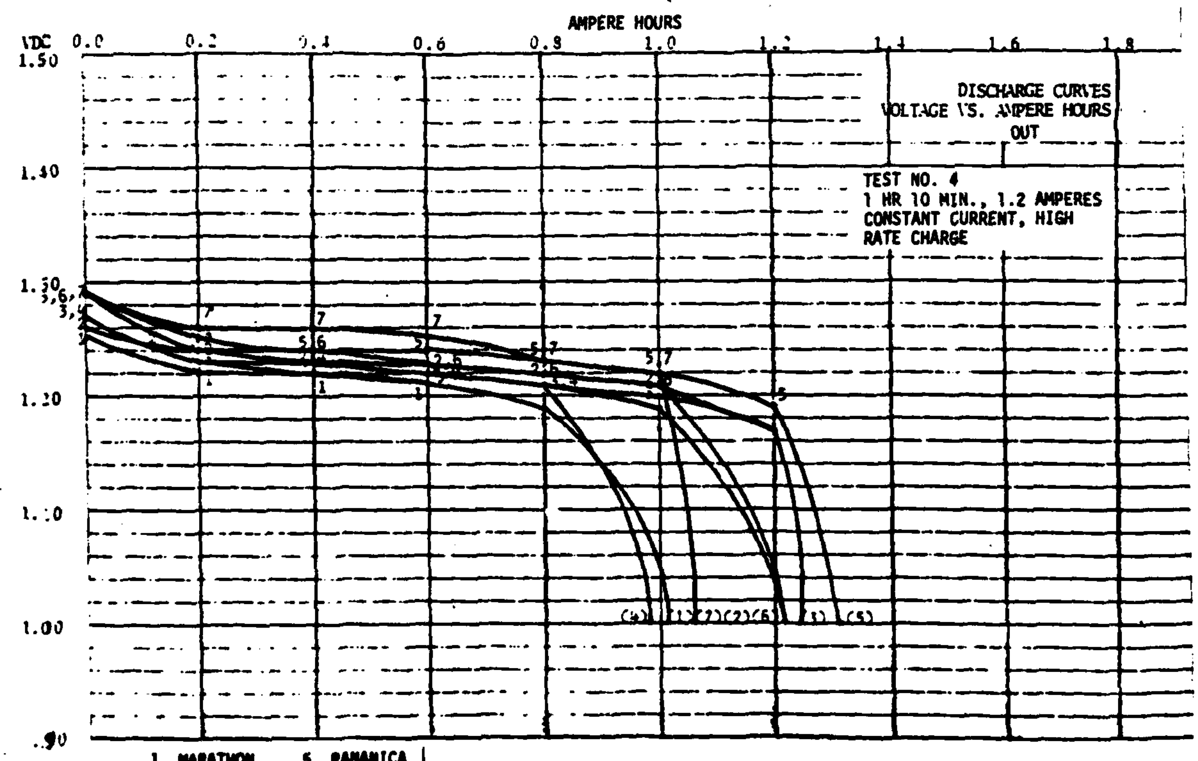
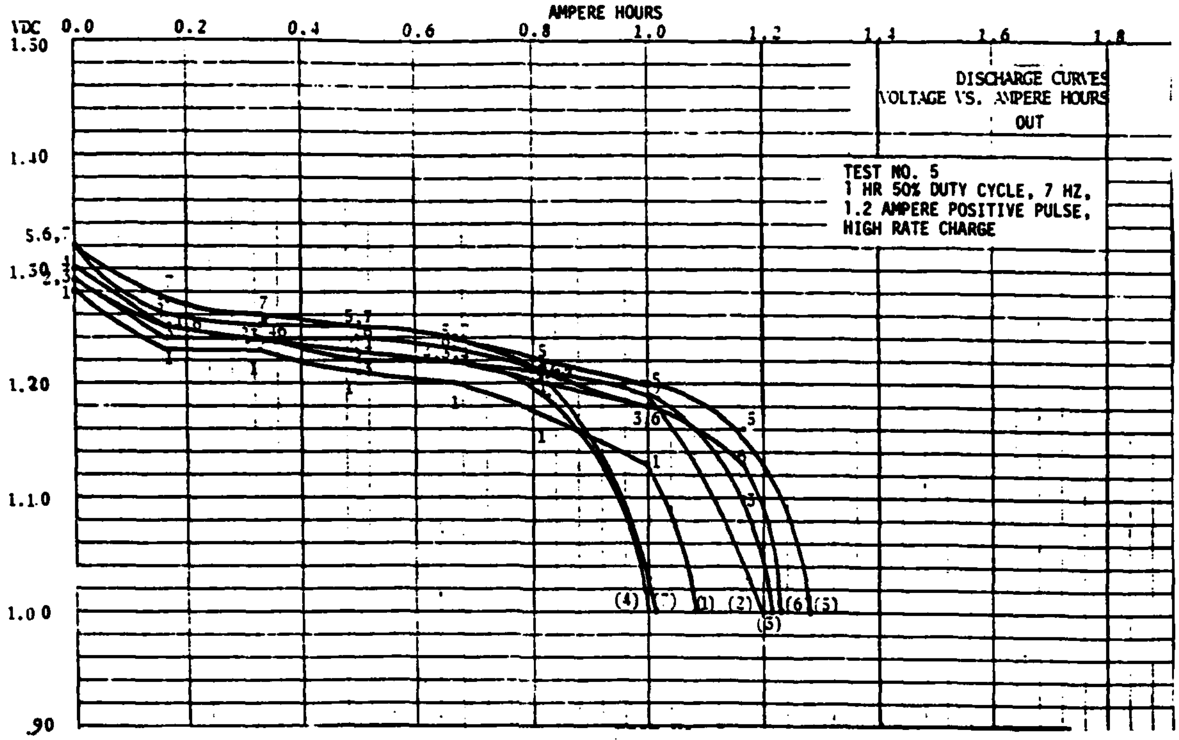
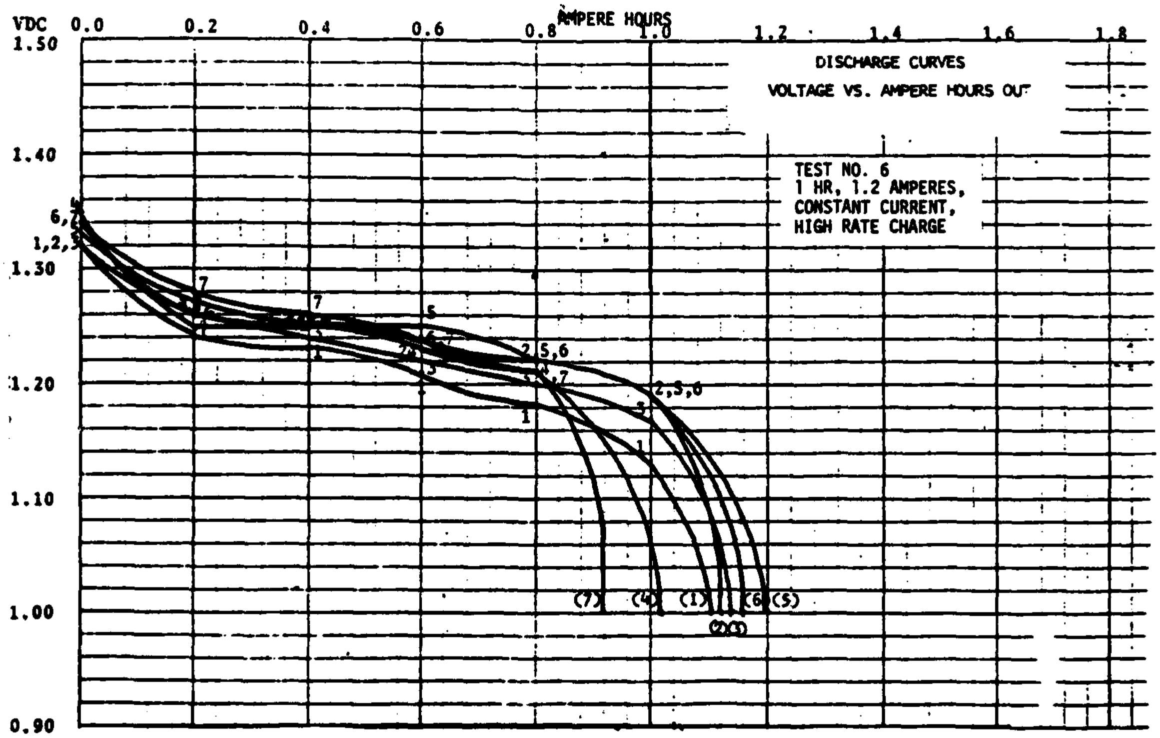


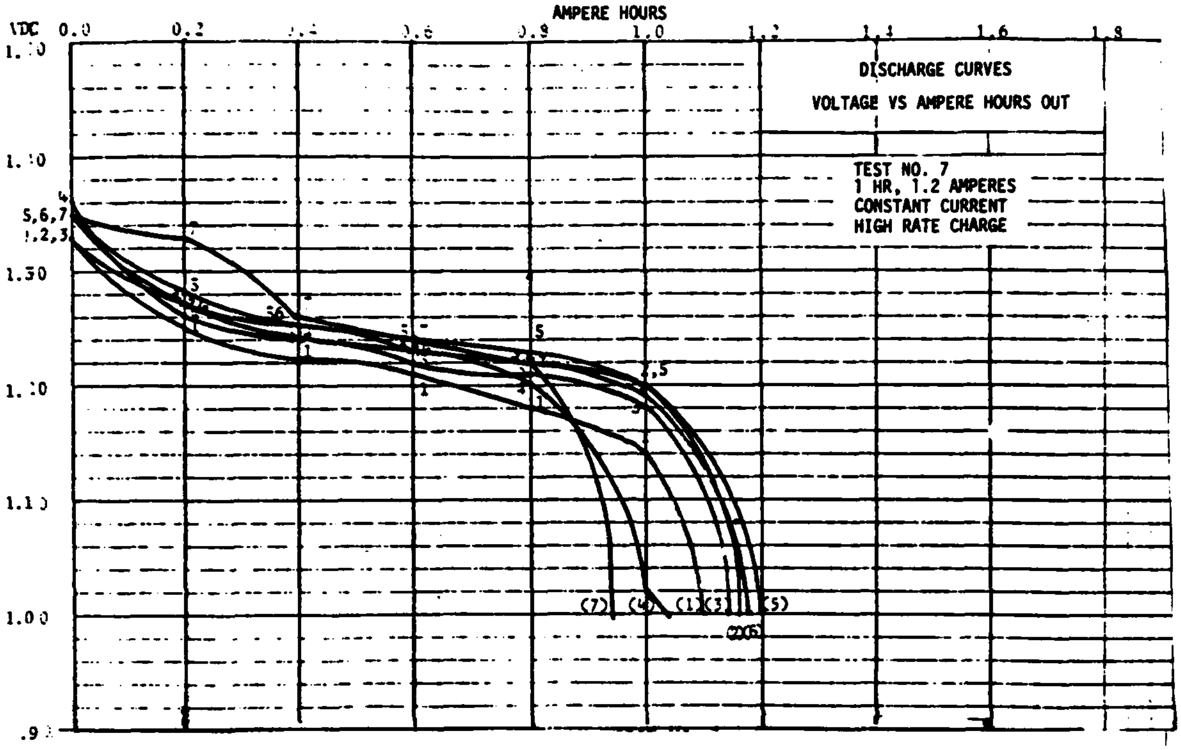


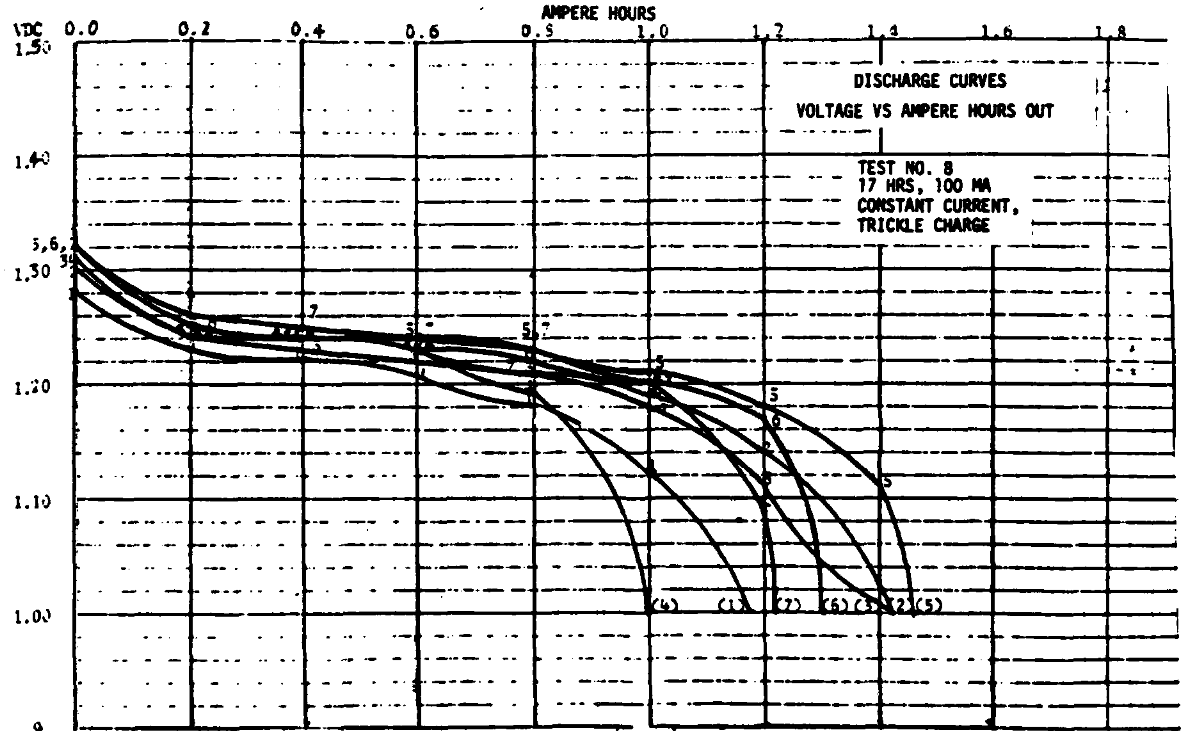
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD





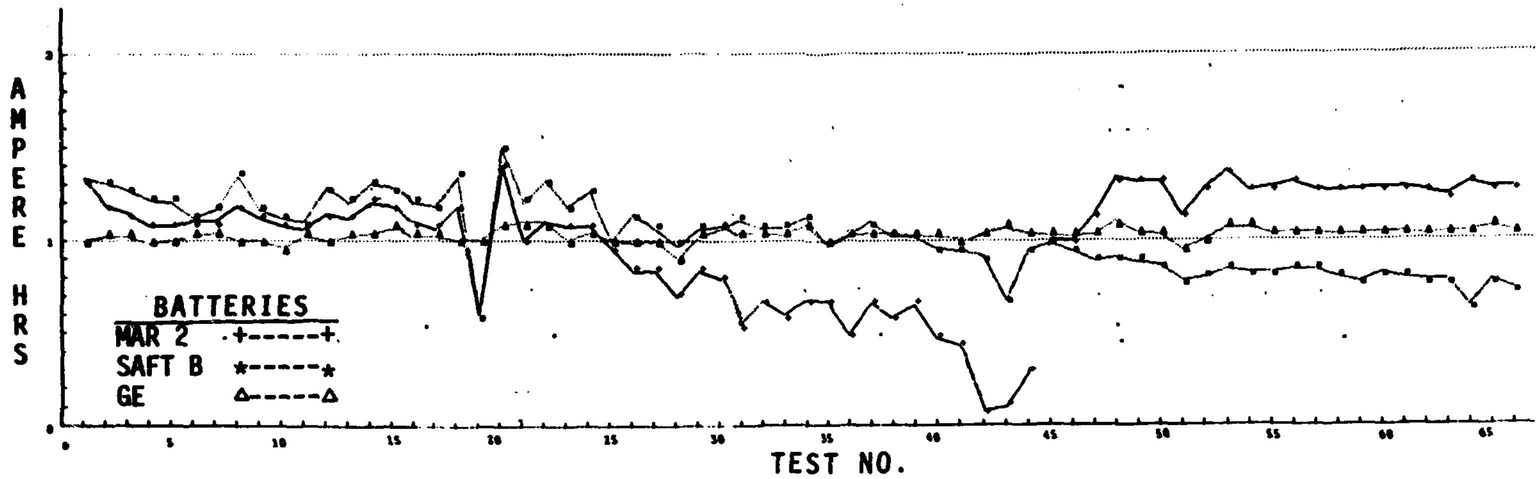
1 - MARATHON 5 - PANANICA
2 - SAFT (BUTT) 6 - SANYO
3 - SAFT (LUG) 7 - GOULD
4 - G.E.

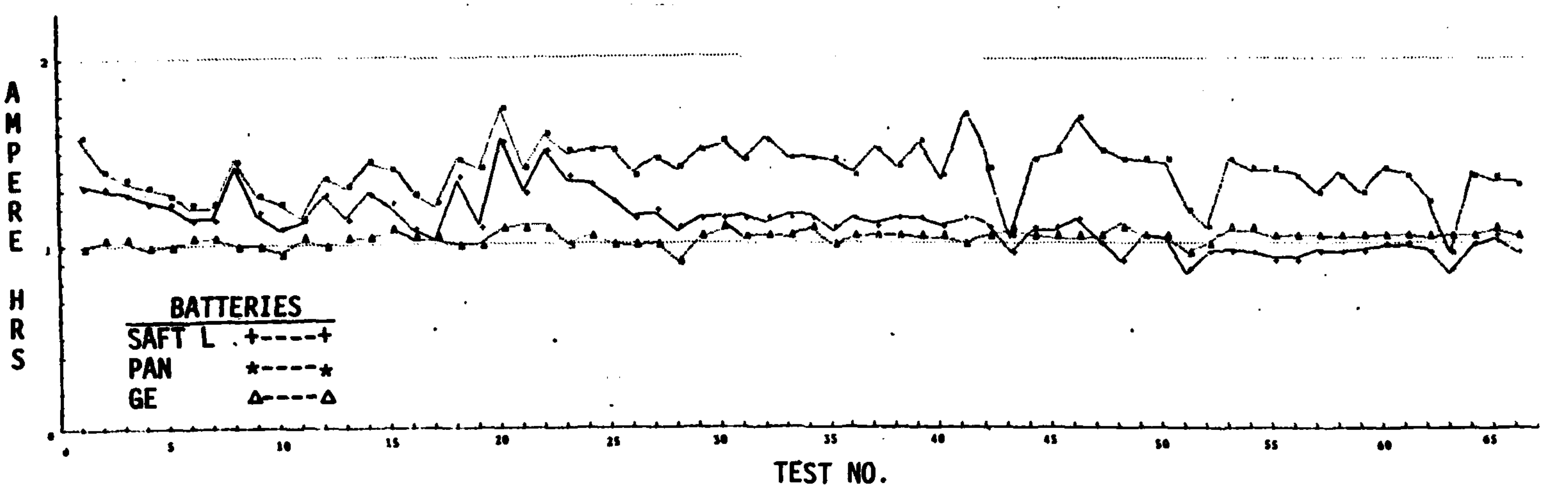


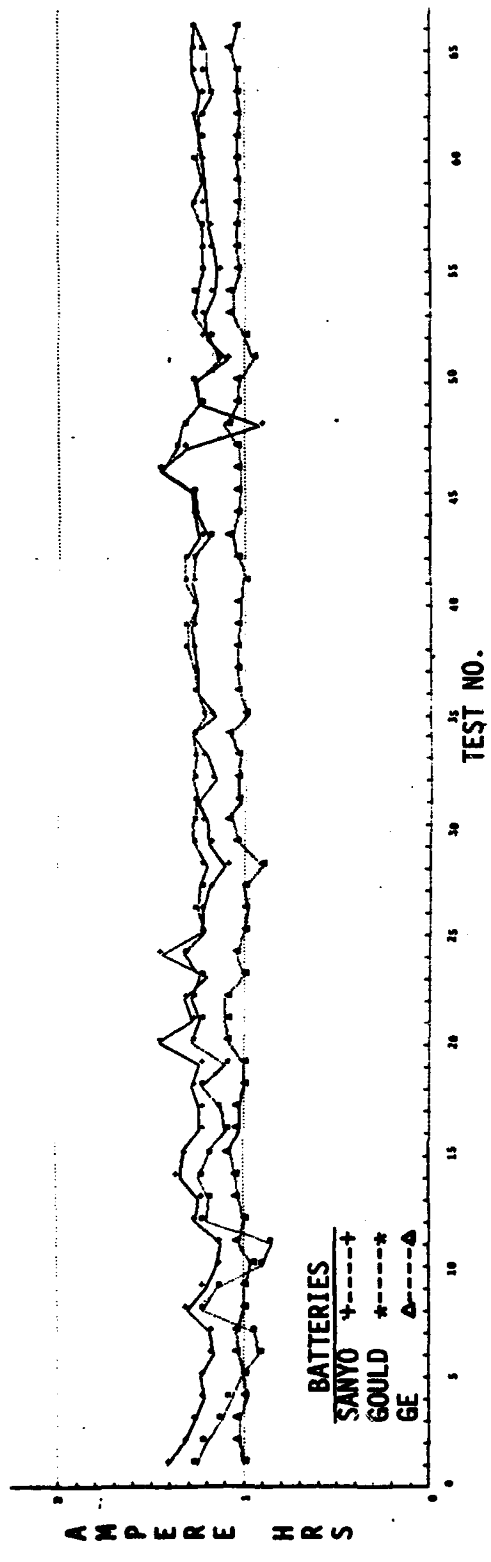


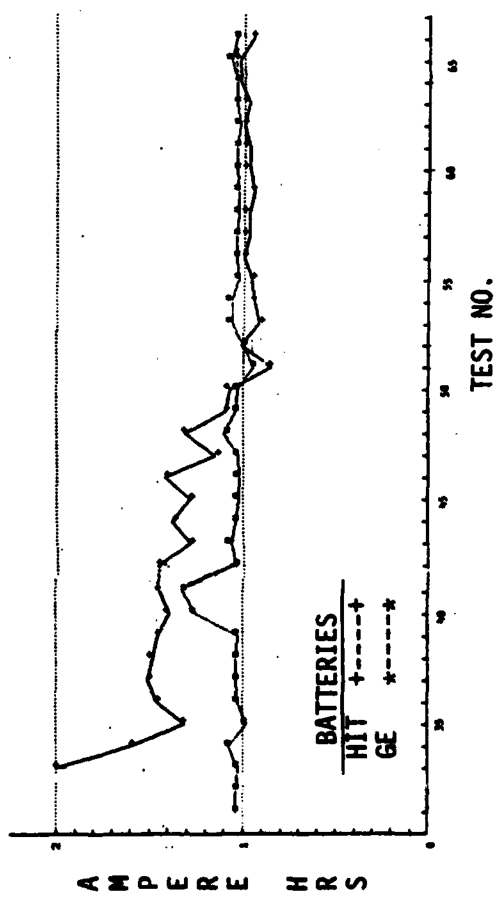
1. MARATHON
2. SAFT (BUTT)
3. SAFT (LUG)
4. G.E.
5. PANANICA
6. SANYO
7. GOULD

APPENDIX E - COMPUTER PLOTS OF OUTPUT CAPACITY






BATTERIES
SANYO +----+
GOULD *----*
GE Δ----Δ
TEST NO.
AMPERE HRS


BATTERIES
HIT +----+
GE *----*
TEST NO.
AMPERE HRS

APPENDIX F - SCATTERED PLOTS OF SMOOTHED DATA

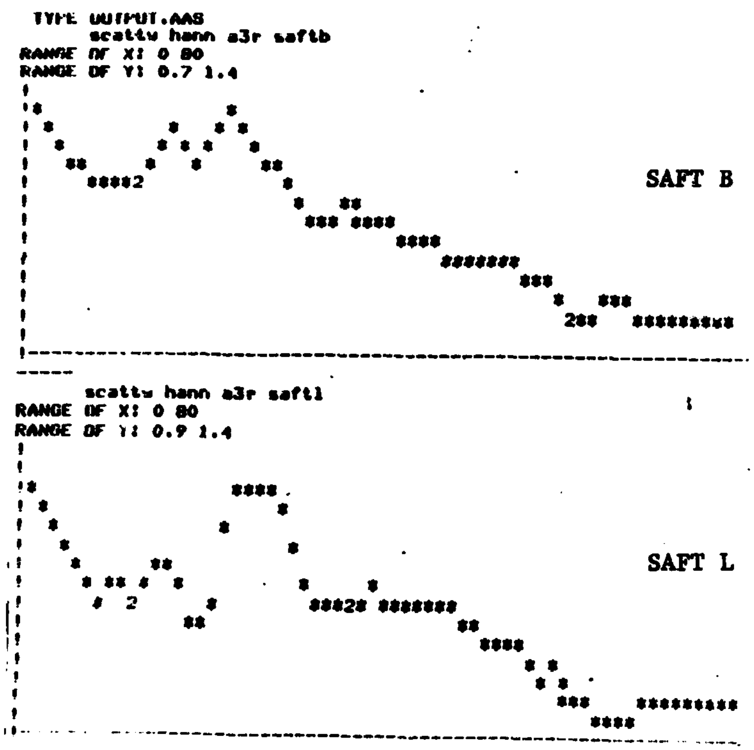


FIGURE F-1. SCATTERED PLOTS OF SMOOTHED DATA FOR SAFT B AND SAFT L CELLS

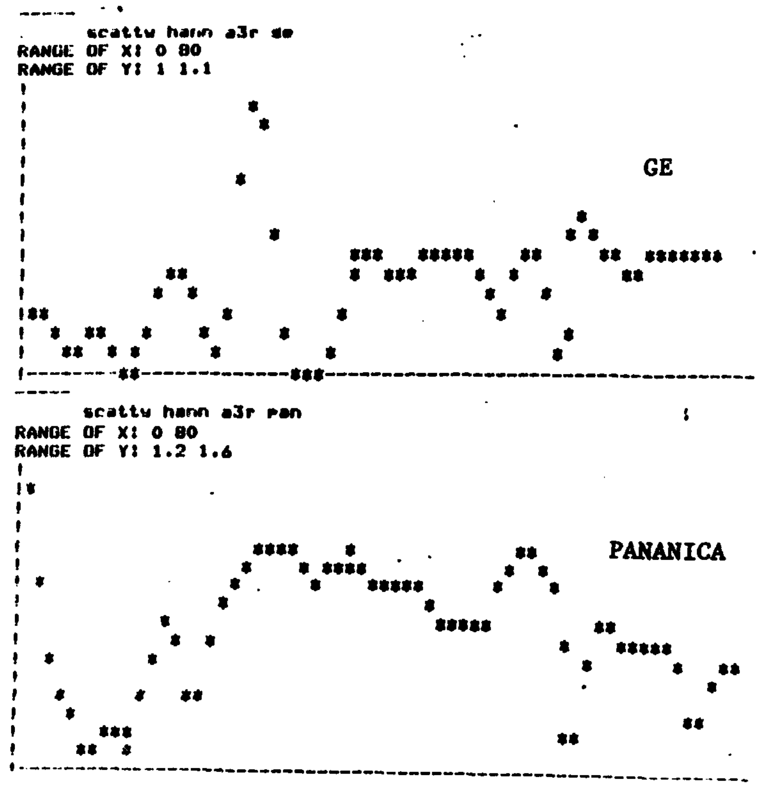


FIGURE F-2. SCATTERED PLOTS OF SMOOTHED DATA FOR GE AND PANANICA CELLS

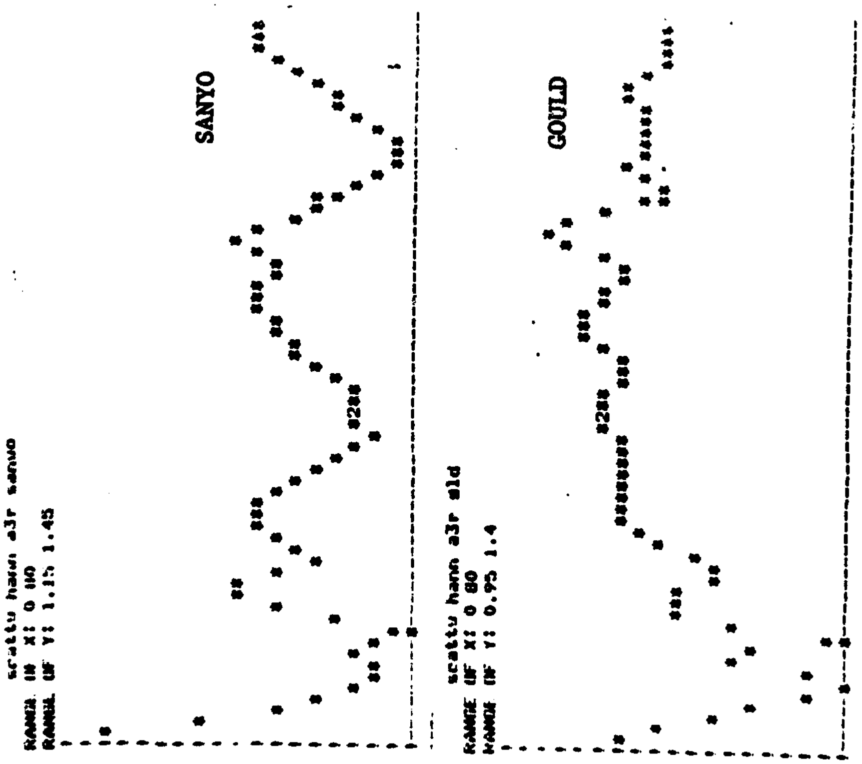


FIGURE F-3. SCATTERED PLOTS OF SMOOTHED DATA FOR SANYO AND GOULD CELLS

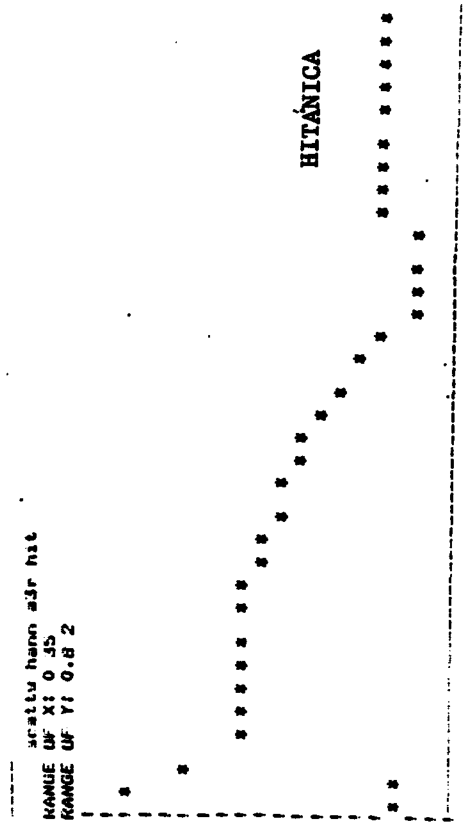


FIGURE F-4. SCATTERED PLOTS OF SMOOTHED DATA FOR HITANICA CELL

APPENDIX G - HISTOGRAM DATA PLOTS

```
TYPE .r.r.aaf
     STEMLEAF SAFTB
06|4
07|37888889
08|00222444689
09|1244567778
10|0022266778
11|0122246688
12|000016688
13|002344
14|
15|0
     STEMLEAF SAFTL
08|33
09|022555556666888
10|122246677889
11|00012233333444444455566
12|01446888
13|02344
14|2
15|06
     STEMLEAF GE
90|0
92|
94|0
96|0
98|000
00|0000000000
02|00000000000000000
04|000000000000000
06|000000
08|00
10|000
     STEMLEAF FAN
09|4
10|27
11|49
12|0002466778
13|01344468888889999
14|00000234445555666666889
15|011124688
16|77
17|2
```

FIGURE G-1. HISTOGRAM DATA PLOTS

```
     STEMLEAF  SANTO
0912
1019
11|02456666668999
12|0000001122334444444455556666777888888888
13|0022224
14|1466
     STEMLEAF  GLD
08|4
09|024
10|16
11|00223478889
12|0000001122222244444445555555555667778888888
13|002236
14|4
     STEMLEAF  HIT
08|52445677777
10|00122795
12|881189
14|2456681
16|0
18|
20|0
     )OUTPUT
```

FIGURE G-2. HISTOGRAM DATA PLOTS

APPENDIX H - PROBABILITY PLOTS

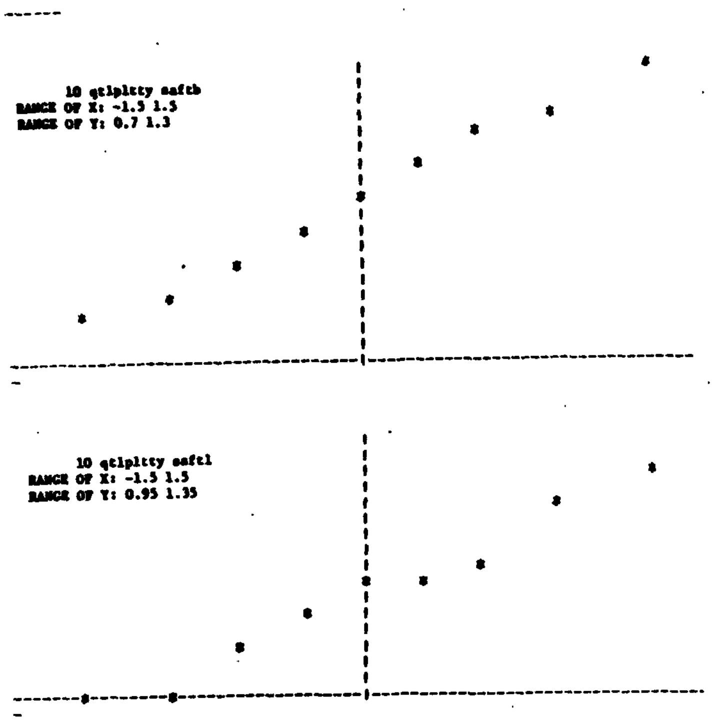


FIGURE H-1. PROBABILITY (NORMALITY) PLOTS

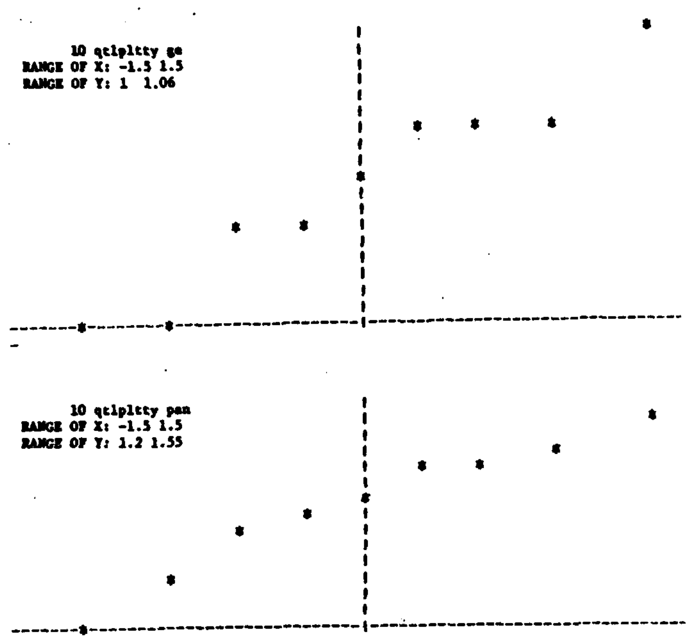


FIGURE H-2. PROBABILITY (NORMALITY) PLOTS

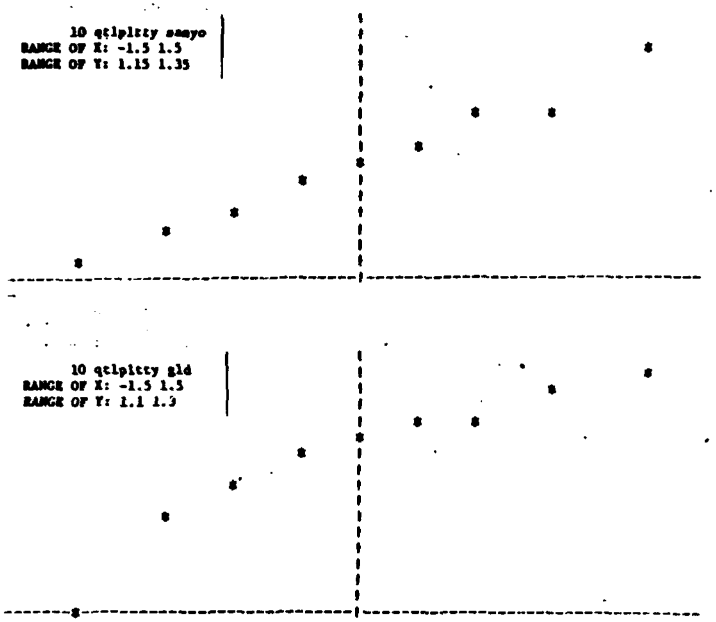


FIGURE H-3. PROBABILITY (NORMALITY) PLOTS

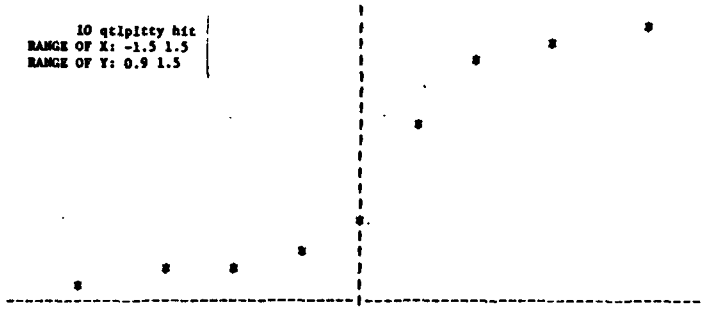


FIGURE H-4. PROBABILITY (NORMALITY) PLOTS

GLOSSARY OF TERMS

auto-transformer........................a transformer that provides a voltage change with no dissipation.

charge pulse magnitude................value in amperes of charge pulse.

charge rate...........................amplitude of charging current.

charging time.........................the time required to achieve the required input capacity for a given charge rate in amperes.

duty cycle............................charging current pulse width as a fraction of repetitious interval.

fixed load resistor...................a resistor of a fixed value selected to control cell discharge at a fixed current.

high rate charging....................charging with high current for a short period of time for a determined capacity input.

McCulloch mode........................is a positive and negative waveform with adjustable duty cycle current amplitude and frequency.

mean..................................the average value of set of data.

pulse frequency.......................cycles per second or hertz.

Romanov mode..........................is an asymmetrical wave form which positive half cycle is different (in duty cycle and current amplitude) than negative half cycle.

smoothed time series..................the discharge data analyzed for an individual cell over the range of tests.

trickle charging......................charging with a low current for a long period of time for a determined capacity input.

variance..............................the variance of a sample is a measure of the spread of data about the mean.

LIST OF ABBREVIATIONS/ACRONYMS AND SYMBOLS

A.......ampere

AH......ampere hour

C.......charge rate

CC......constant current

CPS.....cycles per second

DC......direct current

EXP.....exponential

F.......ratio of variance

GAU.....Gaussian

GE......General Electric

GLD.....Gould

H.......high-rate charging

HIT.....Hitanica

Hz......hertz

T.......low-rate (trickle) charging

MA......milli-ampere

N.......number of observations

PAN.....Pananica

R.......resistor

S.......variance

U.......population parameter

V.......voltage

VAR.....variance

y_i......value of output capacity

$\overline{y}$.......mean value of output capacity